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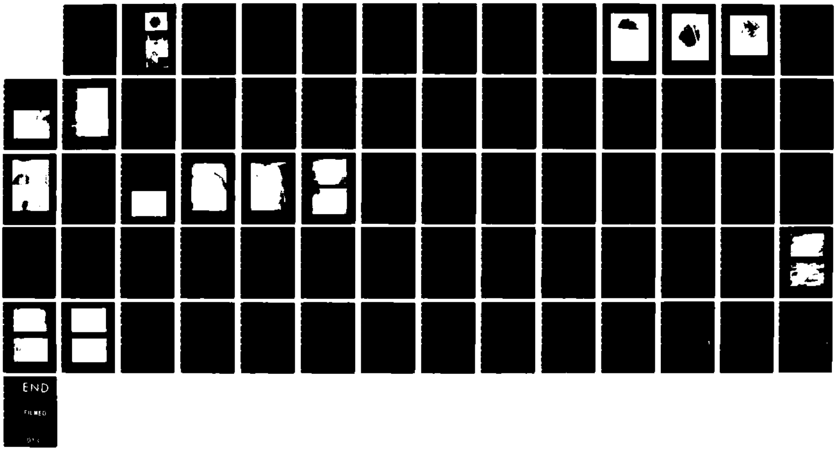

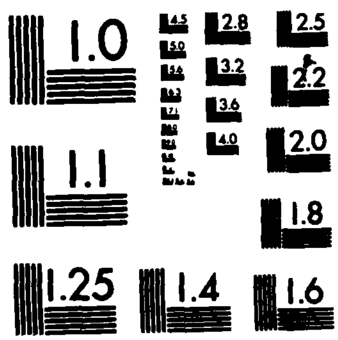

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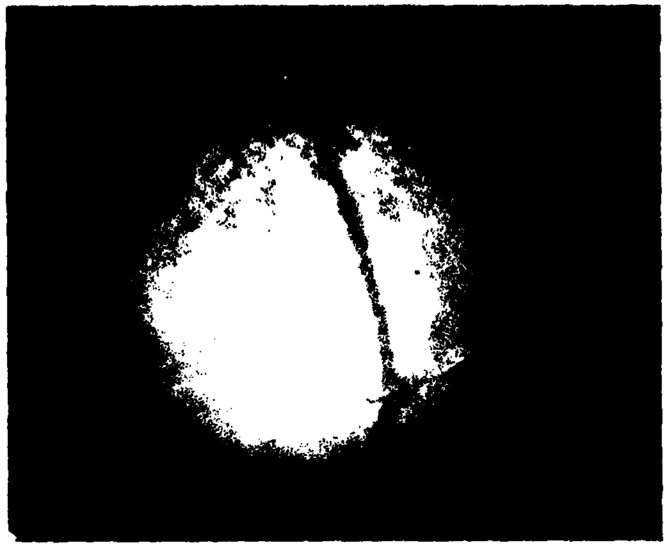
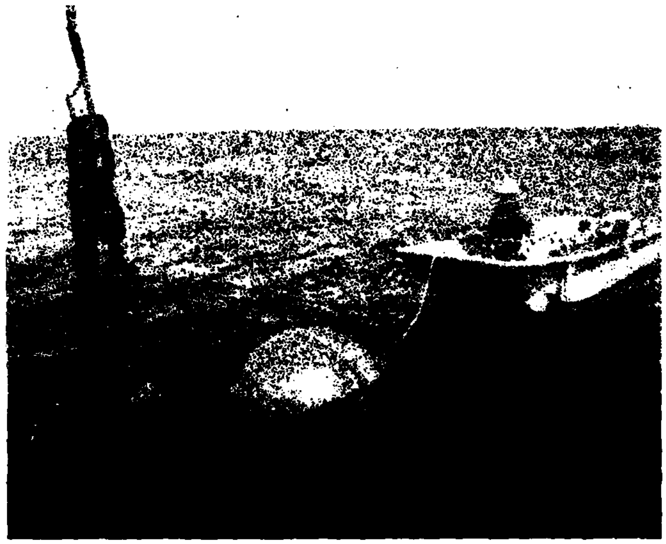
Technical Report R-915

AD-A160 232

Long-Term, Deep-Ocean Test of Concrete Spherical Structures - Results after 13 Years

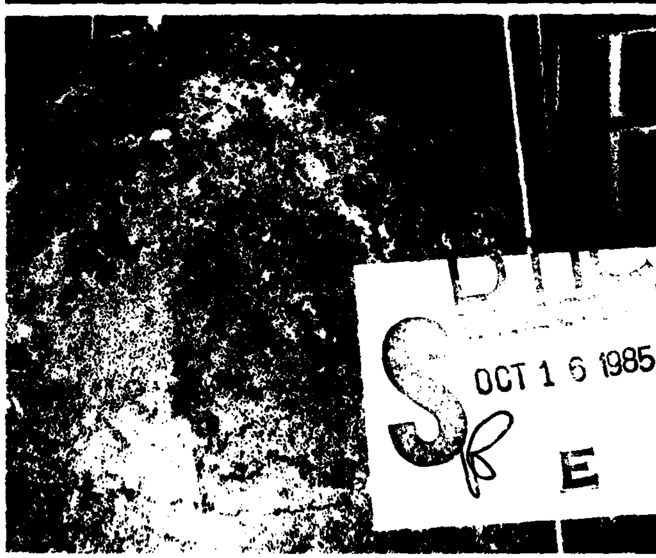




By

R. D. Rail and R. L. Wendt

July 1985



NAVAL CIVIL ENGINEERING LABORATORY
Port Hueneme, California 93043

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NAVAL SEA SYSTEMS COMMAND
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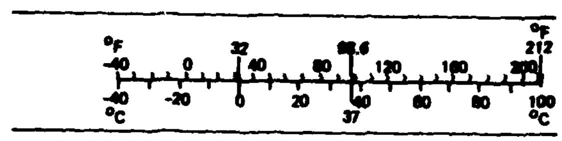
Alexandria, Virginia 22332

CONVERSION FACTORS—INCH-POUND TO SI (METRIC)

Approximate Conversion Factors (E indicates that the factor given is exact)

To convert from	to	multiply by
Length		
inch	millimeter (mm)	25.4E
foot	meter (m)	0.3048E
yard	meter (m)	0.9144E
mile (statute)	kilometer (km)	1.609
Area		
square inch	square centimeter (cm^2)	6.451
square foot	square meter (m^2)	0.0929
square yard	square meter (m^2)	0.8361
Volume (capacity)		
ounce	cubic centimeter (cm^3)	29.57
gallon	cubic meter (m^3)	0.003785
cubic inch	cubic centimeter (cm^3)	16.4
cubic foot	cubic meter (m^3)	0.02832
cubic yard	cubic meter (m^3)	0.7646
Force		
kilogram-force	newton (N)	9.807
kip-force	newton (N)	4448
pound-force	newton (N)	4.448
Pressure or stress (force per area)		
kilogram-force/square meter	pascal (Pa)	9.807
kip-force/square inch (ksi)	megapascal (MPa)	6.895
newton/square meter (N/m^2)	pascal (Pa)	1.000E
pound-force/square foot	pascal (Pa)	47.88
pound-force/square inch (psi)	kilopascal (kPa)	6.895

To convert from	to	multiply by
Bending moment or torque		
inch-pound-force	newton-meter (Nm)	0.1130
foot-pound-force	newton-meter (Nm)	1.356
meter-kilogram-force	newton-meter (Nm)	9.807
Mass		
ounce-mass (avoirdupois)	gram (g)	28.34
pound-mass (avoirdupois)	kilogram (kg)	0.4536
ton (metric)	megagram (Mg)	1.000E
ton (short, 2000 lbm)	megagram (Mg)	0.9072
Mass per volume		
pound-mass/cubic foot	kilogram/cubic meter (kg/m^3)	16.02
pound-mass/cubic yard	kilogram/cubic meter (kg/m^3)	0.5933
pound-mass/gallon	kilogram/cubic meter (kg/m^3)	119.8
Temperature§		
deg Fahrenheit (F)	deg Celsius (C)	$t_C = (t_F - 32)/1.8$
deg Celsius (C)	deg Fahrenheit (F)	$t_F = 1.8t_C + 32$



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In 1971, a long-term, deep-ocean test was started on 18 pressure-resistant, hollow concrete spheres, 66 inches in outside diameter by 4.12 inches in wall thickness. The spheres were placed in the ocean near the seafloor at depths from 1,840 to 5,075 feet. Over a 13-year period, annual inspections of the spheres using submersibles have provided data on time-dependent failure and permeability. After 5.3 years of exposure, three spheres were retrieved from the ocean for laboratory testing, and after 10.5 years two more spheres were retrieved

continued

20. Continued

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1. Undersea concrete structures 2. Concrete spheres I. 3.1610-1

In 1971, a long-term, deep-ocean test was started on 18 pressure-resistant, hollow concrete spheres, 66 inches in outside diameter by 4.12 inches in wall thickness. The spheres were placed in the ocean near the seafloor at depths from 1,840 to 5,075 feet. Over a 13-year period, annual inspections of the spheres using submersibles have provided data on time-dependent failure and permeability. After 5.3 years of exposure, three spheres were retrieved from the ocean for laboratory testing, and after 10.5 years two more spheres were retrieved and tested. This report is the third report in a series describing and summarizing the findings from the ocean and laboratory tests. Data on concrete compressive strength gain, short-term implosion strength of the retrieved spheres, and permeability and durability of the concrete were obtained. The data have shown that concrete exhibits good behavior for ocean applications. High quality, well-cured concrete can be expected to gain and maintain strength when submerged in seawater under high pressure. Concrete is a durable material in the deep ocean; neither deterioration of the concrete matrix nor corrosion of reinforcing steel are problems, even though the concrete becomes saturated with seawater. Uncoated concrete has a very low rate of permeation of seawater through the concrete and even this small flow can be prevented by a waterproofing coating.

CONTENTS

INTRODUCTION

In September 1971 the Naval Civil Engineering Laboratory (NCEL) began an experimental program on the behavior of pressure-resistant concrete spherical structures placed in the deep ocean for long-term exposure to high-pressure seawater. In-situ inspections of the spheres were made annually using manned submersibles over a 13-year period. On two occasions selected spheres were retrieved from the ocean for laboratory testing.

This report is the third in a series documenting the program. Reference 1 described sphere fabrication, ocean emplacement, and early in-situ inspections; Reference 2 presented additional inspection observations and on-land laboratory test results of three spheres and other concrete specimens retrieved after 5.3 years of ocean exposure. This report presents the results from five additional in-situ inspections and laboratory tests on two more spheres (retrieved after 10.5 years of ocean exposure) and on other ocean-exposed and on-land control specimens; a summary of the overall findings to date is included.

This study was supported by the Naval Sea Systems Command and the Naval Facilities Engineering Command as part of the U.S. Navy's "Deep Ocean Technology" program.

OBJECTIVES

The major technical objective of the experimental work was to obtain data on time-dependent strength, permeability, and durability of pressure-resistant concrete spherical structures subjected to sustained high-pressure seawater for extended periods of time. Such data contribute to a technology base from which engineering design guidelines may be prepared. In addition, a purpose of the program was to expose the spheres to real environmental conditions. The findings will aid in establishing confidence in using concrete as a deep ocean construction material.

TEST DESCRIPTION

Overall Approach

Eighteen hollow concrete spheres 66 inches in outside diameter and 4.12 inches in wall thickness were placed in the ocean near Santa Cruz Island, Calif., at water depths of 1,840 to 5,075 feet. The buoyant spheres were tethered about 25 feet above the seafloor by the dead weight of anchor chains. (Each of fourteen of the spheres was anchored by a 2,600-pound, 2-1/4-inch anchor chain 53 feet long; the other four spheres had similar chains of slightly different sizes.)

Sixteen spheres were unreinforced concrete; eight of these were coated on the exterior with a phenolic compound (Phenoline No. 300) to act as a waterproofing agent, and eight were left uncoated. The other two spheres were lightly reinforced with No. 4 (1/2-inch-diam) deformed steel bars with a concrete cover varying from less than 1 to 2.5 inches. Half of the exterior of each of these two spheres was coated with the waterproofing agent. The reason for including the steel reinforcement was not to strengthen the spheres but to investigate the extent to which concrete protects the steel against corrosion in the deep ocean environment.

The ocean depth range for the spheres corresponds to predicted relative load levels of 0.36 to 0.83. The relative load level, P_s/P^p_{im}, is defined as the ratio of sustained pressure to predicted short-term implosion pressure. Time-dependent failure was anticipated for some of the spheres subjected to the higher load levels; therefore, the six deepest spheres had clock mechanisms for recording the day of implosion. If other specimens were to implode, the yearly inspections would discover the failed specimens.

Permeability data were obtained by two methods: by measuring the water found inside the recovered spheres, and by the annual inspections. Each sphere, which was about 950 pounds buoyant, supported about 30 links of its anchor chain off the seafloor. As seawater was absorbed by and permeated through the concrete wall into the interior of the sphere, the sphere weight increased, buoyancy decreased, and less chain was supported. Thus, for the 2-1/4-inch chains, a decrease of one chain link in the number of links between the sphere and the seafloor indicates that about 1/2 ft^3 of seawater has been taken on by the sphere.

Durability data were obtained from spheres, concrete blocks, and cement paste specimens retrieved after exposure for various lengths of time in the ocean and were compared to data from control specimens.

Sphere Fabrication and Control Specimens

Concrete hemispheres were cast, one at a time, in a steel mold, demolded after 24 hours, moist-cured for 28 days, and field-cured for several weeks. Each sphere was fabricated from two hemispheres bonded together by an epoxy adhesive at their equatorial surfaces, which had been ground flat.

The concrete mix contained 7.8 sacks of Type II cement per cubic yard with water/cement, sand/cement, and coarse aggregate/cement ratios (by weight) of 0.40, 1.85, and 2.28, respectively. Maximum aggregate size was 3/4 inch. Average unit weight of the fresh concrete was 145 lb/ft^3, and average slump was 1-1/2 inches.

Twelve 6- by 12-inch-long control cylinders and one 18- by 18- by 14-inch-thick control block were cast from the same batch of concrete along with each hemisphere. (None of the control cylinders or blocks were coated with the waterproofing agent.) Half the cylinders were continuously cured in a 73°F 100% relative humidity fog room until their eventual compressive strength tests. The other cylinders and the blocks were field-cured along with their respective hemispheres (wrapped in plastic sheeting and moist-cured 28 days, then atmosphere-exposed); these cast cylinders were tested at the time the spheres were deployed in the ocean to estimate the strength of the concrete in the spheres at

the time they were placed in the deep ocean. One block for each sphere was deployed with that sphere in the ocean by attaching the block to the sphere's anchor chain a few links below the sphere. The second block for each sphere was stored outdoors on land about 150 feet from the ocean until eventual testing.

Ocean-exposed blocks retrieved after various times in the ocean were drilled to produce four cylindrical cores, nominally 6 inches in diameter by 12 inches long, from each block. The cores, along with similar cores from the on-land, field-exposed blocks, were tested at the same time as the fog-cured cast cylinders.

AT-SEA OBSERVATIONS

In-Situ Inspection by Submersibles

Twelve cruises have been made to date to inspect the spheres in place. All but one cruise were made by the U.S. Navy's Submarine Development Group One, San Diego, Calif., using manned, free-swimming submersibles DSV-3 TURTLE and DSV-4 SEACLIFF and rescue vehicle DSRV-2 AVALON. The Scripps Institution of Oceanography inspected three of the deeper spheres in 1972, using the unmanned, bottom-crawling Remote Underwater Manipulator (RUM).

Each inspection operation consisted of a number of dives from a surface support vessel to inspect as many spheres as possible within the time and weather limitations. Inspection at each sphere included visual observations, photographs (e.g., Figures 1 and 2), and chain link counts. The number of spheres inspected during an individual cruise has varied from 3 to 14; thus, some spheres have been inspected more frequently than others. Sphere No. 6 has not been inspected. Table 1 presents data obtained during the inspections.

Several of the spheres (e.g., No. 15, 17, and 18) show chain link counts that increased with time. These increases are assumed to be discrepancies in the count due to poor visibility, turbidity, and fouling on the chain, which in some cases makes it difficult for the submersible operators to discriminate the individual links. Also, at the close range that is needed to pick out individual links, only some of the links being counted are in the field of view at one time. Thus, the submersible operator, especially in a DSV, has the difficult job of maintaining an accurate chain count while simultaneously navigating the submersible vertically up and down the chain, maintaining the correct heading and horizontal position against currents, and avoiding stirring up turbidity from the seafloor, all while in close proximity to the chain and sphere and to the seafloor. The DSRV also requires skillful maneuvering to inspect objects near the seafloor, but it has a better capability to hover and move vertically near the seafloor without stirring up turbidity. Also, the chain under observation can be displayed on the vehicle's television viewing screens so that more than one individual can count simultaneously, thus providing better accuracy.

The recent in-situ inspections have revealed a considerable increase in the amount of the biological fouling on both the coated and uncoated concrete spheres and on the steel anchor chain. Also, the size of individual coelenterate-type animals is much larger as may be seen in Figure 3.

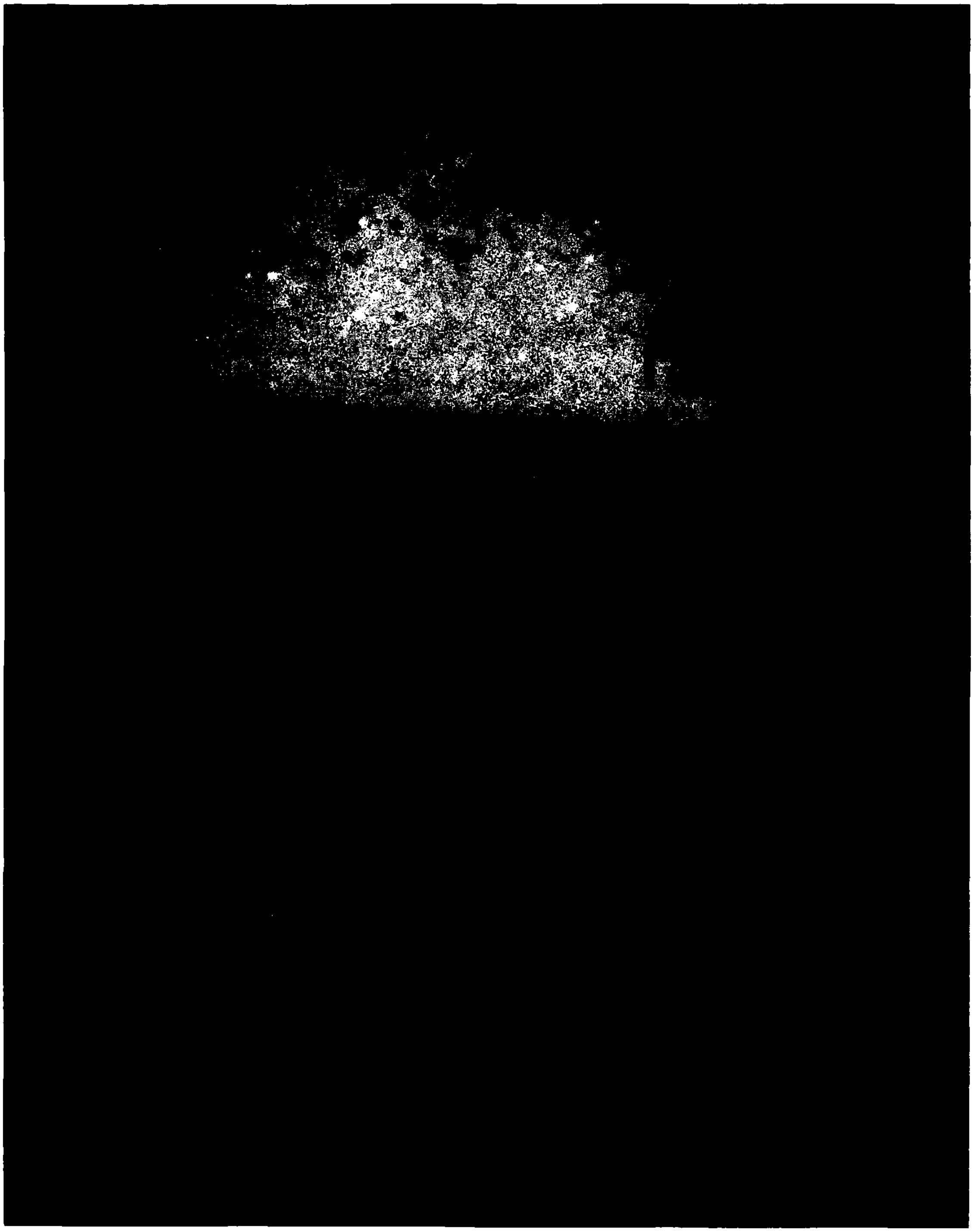

Figure 1. Sphere No. 18 in place in ocean.

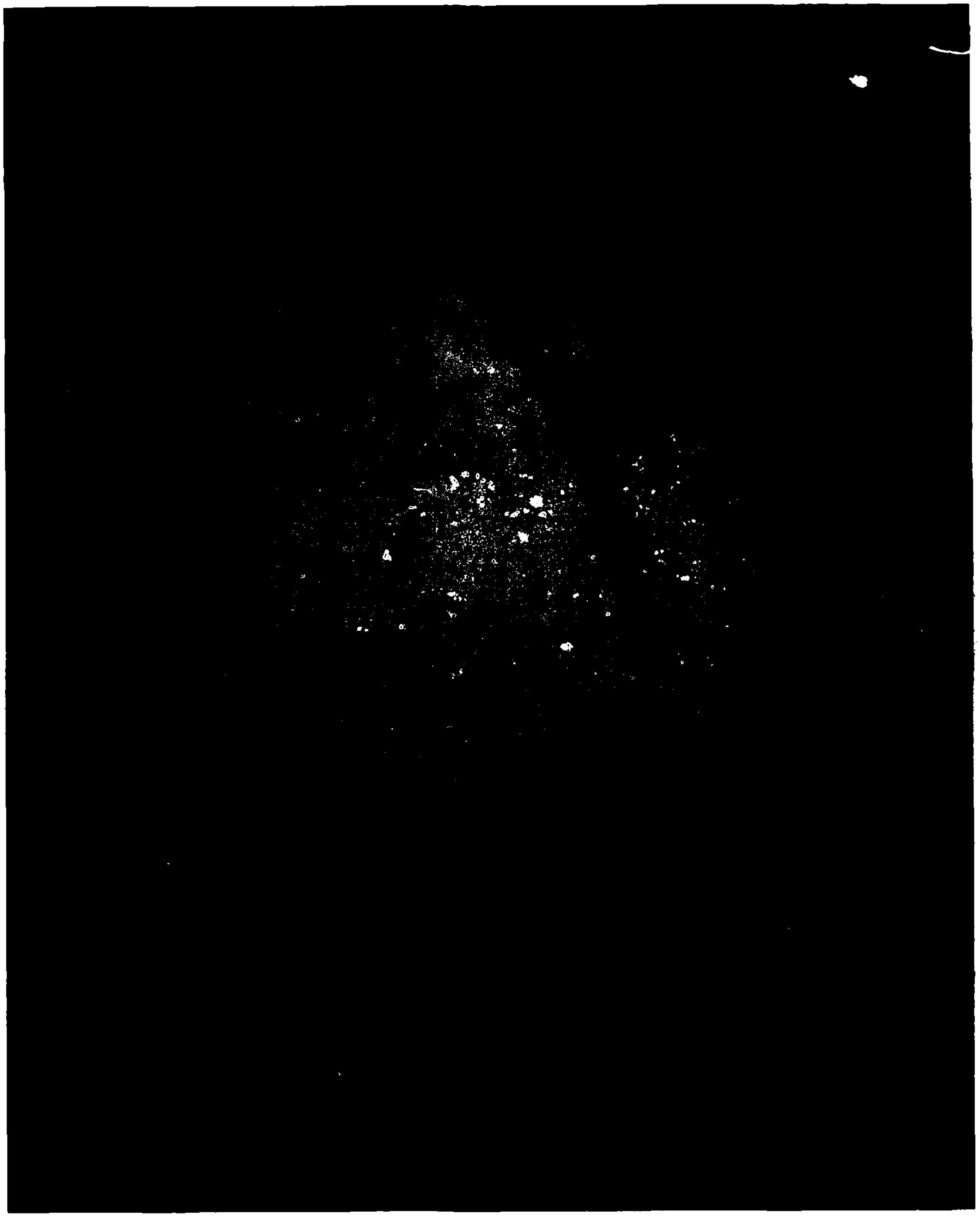

Figure 2. Sphere No. 10 in place in ocean.

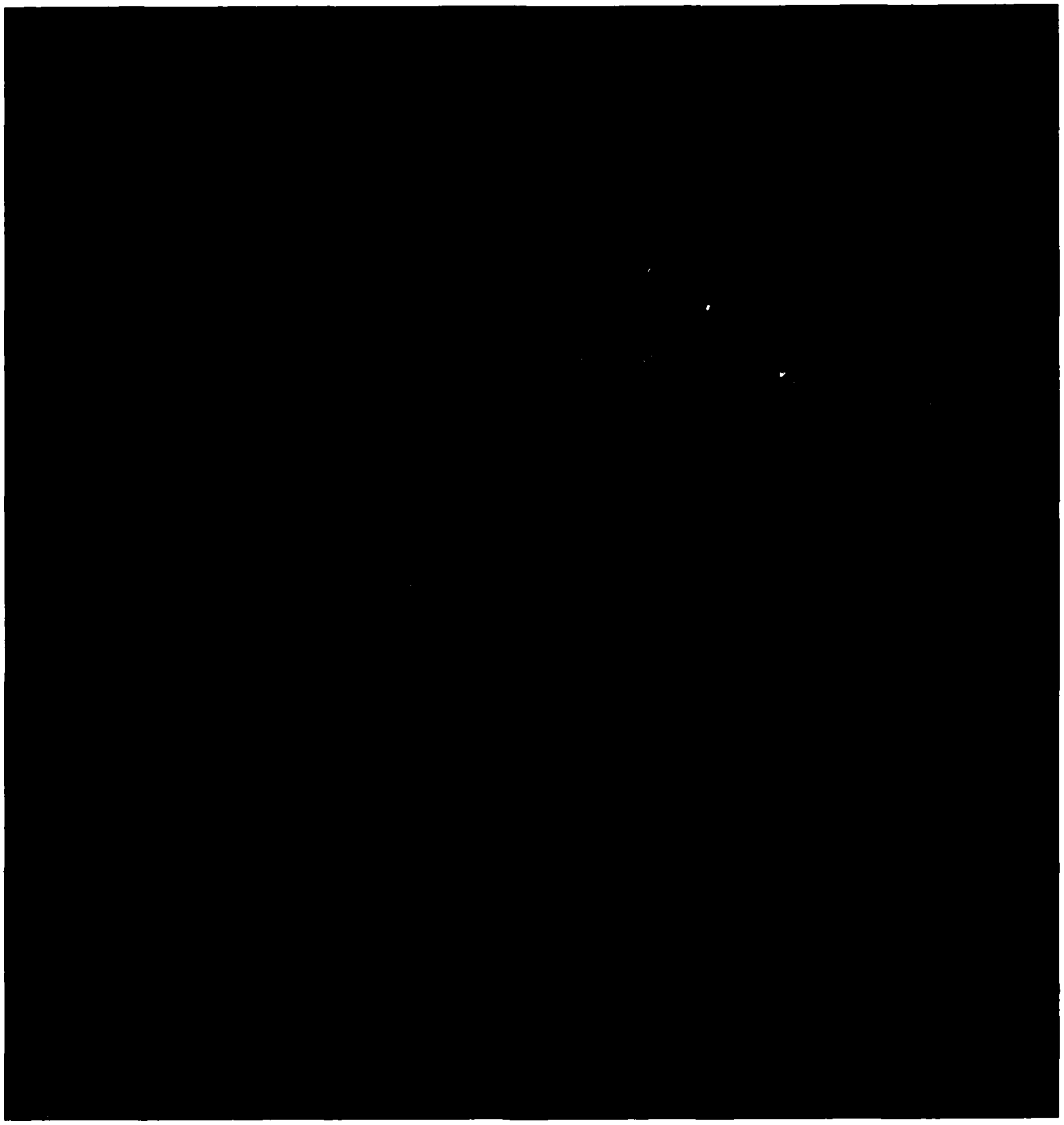

Figure 3. Fouling on Sphere No. 17 after 10 years in the ocean.

Table 1. Sphere In-Situ Inspection Data

Sphere No.	Exterior Surface	Sphere Deployment 23 Sep 1971		Observed Number of Chain Links Off S					
		Depth (ft)	Assumed Chain Link Count at Start of Test[a]	Inspection No. 1 (Mar 1972, 163 Days)	Inspection No. 2 (Aug 1972, 340 Days)	Inspection No. 3 (Dec 1972, 431 Days)	Inspection No. 4 (Nov 1973, 776 Days)	Inspection No. 5 (Oct 1974, 1,120 Days)	Inspection No. 6 (Jan 1977, 1,945 Days)
1	coated	5,075	29.7					imploded	
2	coated	4,875	29.7					no count[b]	27
3	coated	4,330	29.4		imploded				
4	uncoated	4,185	29.4		23			no count[b]	22
5	uncoated	4,100	29.6		21			no count[b]	18
6[c]	uncoated	3,875	29.6						
7	coated	3,725	31.5			imploded			
8	coated	3,665	31.5			intact but on bottom[d]			
9	uncoated	3,295	31.6			chain tangled[e,b]			intact[e,b]
10	uncoated	3,190	31.6			24	24		23
11	coated	3,140	34			31	31		30-1/2[g]
12	uncoated	2,790	31.7			24	24-1/2	24-1/2	24-1/2[g]
13	coated	2,635	32.1	28		28	29	29	29[g]
14	coated	2,440	43	39		39	38-1/2	38-1/4	38
15	uncoated	2,300	32.2	26		25	25-1/2	25-3/4	25
16	uncoated	2,120	31.8	26		25	25	24	23
17	half-coated	1,980	32.6	29		28		29	
18	half-coated	1,840	32.6			25			21

[a]Number of chain links between sphere and seafloor calculated from known weights of components based on "air-drie

[b]Sphere intact and floating.

[c]Not inspected to date.

[d]Sphere flooded, probably from leak.

[e]Chain tangled; could not count links.

[f]Retrieved during Inspection No. 10.

[g]Retrieved during Inspection No. 6.

[h]Sphere has small (about 4-inch diameter) hole in top, but did not implode.

1 of 2

Sphere and Sample Retrievals and Visual Examinations

During the 10th inspection cruise in March 1982, two more spheres (No. 10 and 18), along with their associated concrete blocks, were retrieved from water depths of 3,190 and 1,840 feet after 10.5 years in the ocean. The submersible TURTLE attached retrieval lines to the anchor chains of the spheres, which were later recovered by the NCEL Ocean Research Craft (Figures 4 and 5). Line attachment and recovery operations were similar to those of 1977, which are described in more detail in Reference 2.

Surface inspection of the retrieved spheres revealed, in general, the same type but considerably greater amounts of the tubeworms, grass-like animal growth, and coelenterata found 5 years earlier. The tube-worm and "grass" growth on the upper surfaces of Sphere No. 18, which was coated, and Sphere No. 10, which was uncoated, was about the same, and in both cases it was heavier than the growth on the uncoated lower hemispheres. Both steel chains had considerably more grasslike growth than the concrete surfaces did. More coelenterata were found on Sphere No. 18 (at 1,830 feet) than on Sphere No. 10 (at 3,190 feet); on Sphere No. 18 most of the coelenterata were attached to the uncoated lower hemisphere.

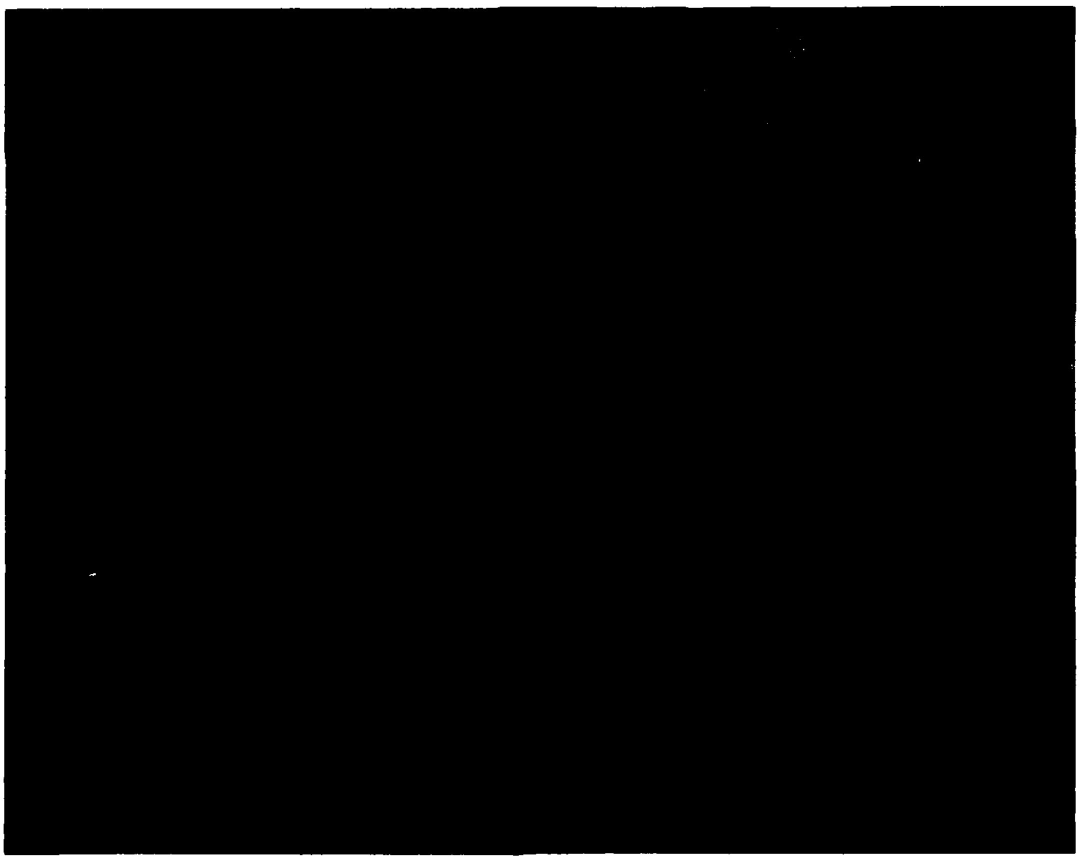

Figure 4. Submersible attaching lifting line to sphere No. 10 anchor chain.

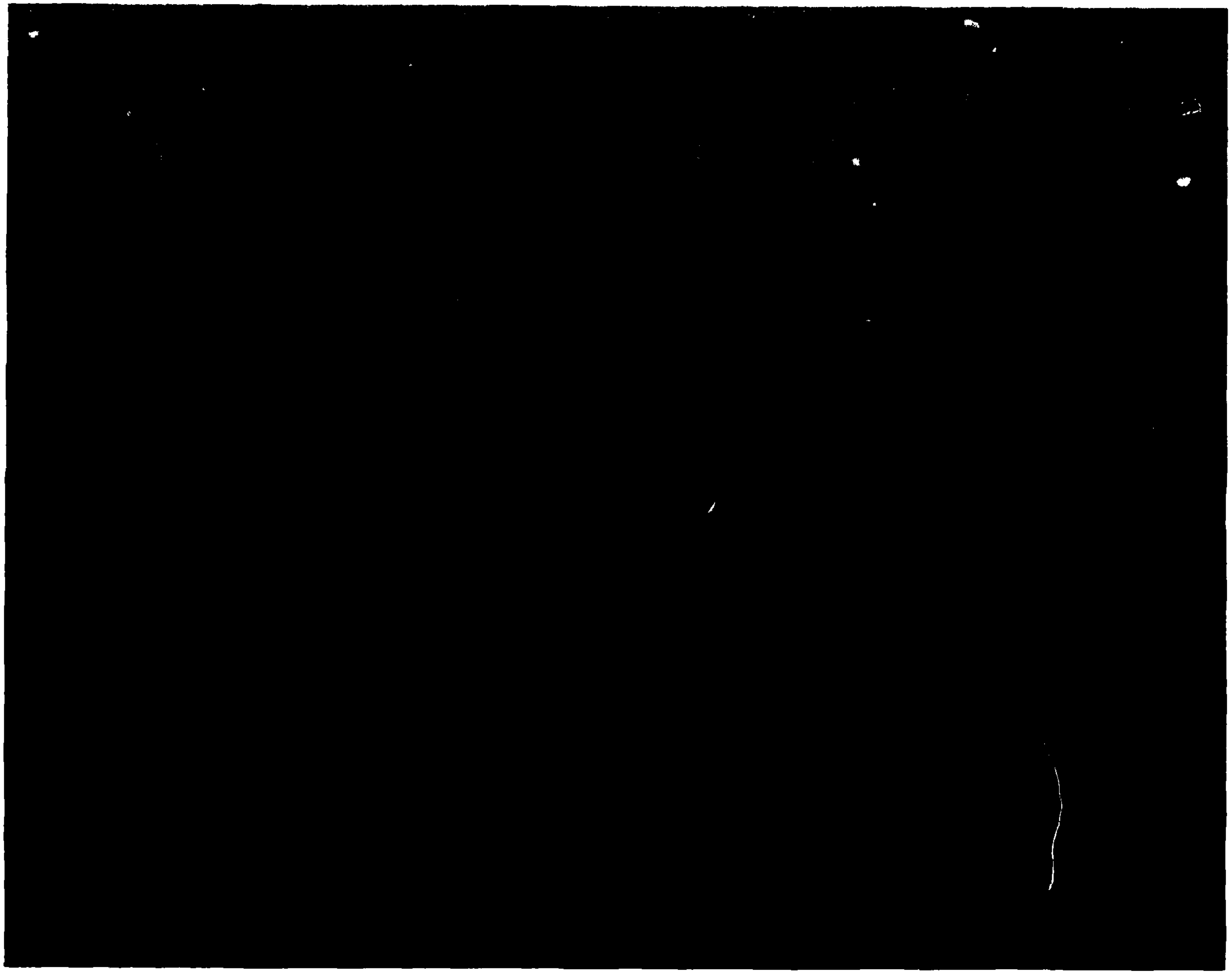

Figure 5. Surface retrieval operation.

At the Sphere No. 15 site the TURTLE recovered a 4-foot-long steel hook with four (of the original five) cement paste samples still attached. The TURTLE operators carefully searched the Sphere No. 16 site but were unable to find either the hook or any of the paste samples that had been placed there. The two sets of cement paste samples had been deployed by the SEACLIFF in March 1978, as described in Appendix D of Reference 2.

The recovered cement paste samples, which had been lying on the seafloor rather than being supported in the water column as originally planned, along with replicate control specimens continuously fog-cured on land, were examined at the University of California, Berkeley, Calif., for possible chemical changes. The results are presented in Appendix A.

Spheres Still in Ocean

Of the original 18 spheres, 5 have been retrieved for laboratory tests, 3 have imploded in the ocean, and 2 have flooded, but not imploded, and are lying on the seafloor (one of them has a local failure near the top of the sphere, possibly at a penetration; the other has no externally visible failure).

Seven intact spheres remain floating just above the seafloor in ocean depths from 1,980 to 4,875 feet. Two of these spheres are coated, four are uncoated, and one is half-coated. Both coated spheres--No. 14, inspected eight times, and No. 2, inspected four times--have had consistent chain link counts with essentially no change since their initial in-situ inspections. Of the uncoated spheres, No. 15 has been inspected 11 times, No. 16 ten times, and No. 5 five times; No. 9 has been observed twice floating off the bottom but has a tangled chain so that no link counts were made. Sphere No. 17, which is half-coated and has 1/2-inch steel reinforcing bars, has been inspected eight times.

TEST RESULTS

Concrete Strength Gain

Comparative uniaxial compressive strength tests were performed in accordance with American Society for Testing Materials (ASTM) Designation C-39 (except as noted below) on nominally 6- by 12-inch concrete cylindrical specimens of 10.8 years total age exposed in three different environments: (1) 10.8 years in continuous fog-room conditions, (2) 10.5 years near the seafloor in the ocean at depths of 1,800 and 3,200 feet, and (3) 10.7 years in the natural outdoor atmosphere on land about 150 feet from the shoreline. For additional information on the three environments see Appendix B. The 6- by 12-inch fog-room-exposed cylinders had been cast at the same time the spheres were fabricated. The ocean- and outdoor-atmosphere-exposed specimens were uncoated concrete blocks 18 by 18 by 14 inches. Four cores 5-3/4 inches in diameter by 12 inches long were drilled from each block shortly before testing. The fog-cured and ocean-exposed specimens were tested in the saturated condition; the on-land specimens were tested in the air-dried condition.

Compressive strength results for this series of tests are presented in Tables 2a and 2b, along with results of tests conducted at 1.3 and 5.6 years total age as previously reported in Reference 2.

To adjust for the compressive strength reduction due to coring, the measured compressive strengths of the cored specimens were increased by 7%, which is the same adjustment factor used in the earlier reports of this program. The rationale for the adjustment is discussed in Appendix A of Reference 2. Table 2a presents measured and adjusted values for compressive strengths of cored specimens, and Table 2b presents the relative compressive strength test results. The following analysis in this report is based on the adjusted values.

Changes in the compressive strengths after exposure for various lengths of time in each of the different environments are presented graphically in Figures 6 through 8. Relative strength is defined as the ratio of the compressive strength of the concrete at a given total age compared to the baseline compressive strength at 28 days of fog-cured cast cylinders. The baseline strengths, nominally 8,000 psi, ranged from 7,240 to 8,620 psi.

The mean relative strengths of the continuously fog-cured specimens increased to 1.23 at 1.3 years, to 1.35 at 5.6 years, and were still essentially the same (1.36) at 10.8 years total age. This pattern of strength gain at early ages followed by a slowing down and then plateauing at later ages is typical of concrete.

The on-land, atmosphere-exposed concrete, tested in the air-dried (partially saturated) condition, at first showed similar but smaller gains, as expected, to mean relative strengths of 1.09 at 1.3 years and 1.32 at 5.6 years, but had an apparent 10% drop in relative strength to 1.21 at 10.8 years total age. This decrease was not anticipated and may have been influenced by differences in the degree of saturation of the concrete at the times of testing, which is controlled by the available moisture, which varied with daily, seasonal, and annual weather conditions as discussed in Appendix B. The measured strength of concrete is sensitive to the degree of wetness or dryness of the concrete at the time of testing; dry concrete has a compressive strength as much as 10% or more greater than that of saturated concrete (Ref 2 and 3).

The ocean-exposed concrete had a somewhat different pattern of strength changes during its early exposure in the ocean. As discussed in detail in Reference 2, this concrete's strength decreased about 10% when first placed in the ocean. This decrease is considered to have been due to the concrete changing in a short period of time from an air-dried condition at the time of deployment (after its initial 28-day moist cure it had been stored outdoors several months until deployment) to a saturated condition in the ocean. However, after the initial loss in strength the concrete continued to cure in the ocean and to gain strength so that after about 1 year in the ocean (total age of 1.3 years) its strength was almost equal (97%) to that of the reference concrete. By 5.6 years total age its mean relative strength was 1.15, and at 10.8 years it was still 1.15. Thus, the ocean-exposed concrete, after an initial loss, gained strength and then leveled off at the later age, much the same as the reference continuously fog-cured concrete, but at a lower attained strength at a given age.

Table 2a. Compressive Strength Test Results for T

Item	Uniaxial Compressive Strength,												
	Sphere No. 3				Sphere No. 11				Sphere No. 12				Sp
	W-15[a]		W-16		W-24		W-21		W-32		W-29		W-26
	f'_c (psi)	COV (%)	f'_c (psi)	COV (%)	f'_c (psi)	COV (%)	f'_c (psi)	COV (%)	f'_c (psi)	COV (%)	f'_c (psi)	COV (%)	f'_c (psi)
Continuous fog-cured cast cylinders[b] with age at test:													
28 days	8,520	1.5	8,400	1.9	7,540	3.8	7,720	2.7	7,570	0.6	7,240	3.0	8,070
1.3 yr	10,470	3.9	10,360	1.5									
5.6 yr					10,960	3.3	10,710	2.1	10,210	4.2	10,160	2.8	10,950
10.8 yr													
Cores[c] from cast blocks field-exposed on land with age at test:													
1.3 yr (includes 28-day moist cure)	9,260[d] (8,650)[e]	3.7											
5.6 yr (includes 28-day moist cure)							9,200 (8,600)	2.0			10,370 (9,690)	2.9	
10.8 yr (includes 28-day moist cure)													
Cores[c] from ocean-exposed cast blocks with age at test:													
1.3 yr (includes 28-day moist cure, on-land field exposure, and 341 days submerged)			8,130 (7,600)	4.0									
5.6 yr (includes 28-day moist cure, on-land field exposure, and 1,950 days submerged)					8,320 (7,780)	3.9			9,960 (9,310)	1.9			9,060 (8,470
10.8 yr (includes 28-day moist cure, on-land field exposure, and 3,850 days submerged)													

[a]Hemisphere identification number.

[b]Average of three 6- by 12-in. cast cylinders.

[c]Average of four nominally 6- by 12-in. cylinders cored from uncoated concrete blocks, 18 by 18 by 14 in.

[d]Adjusted core strength; see DISCUSSION in text.

[e]Measured core strength.

essive Strength Test Results for Test Specimens From Concrete Batches Used in Spheres

Uniaxial Compressive Strength, f'_c and Coefficient of Variation, COV for---																
Sphere No. 12				Sphere No. 13				Sphere No. 1				Sphere No. 10				Sphe
W-32		W-29		W-26		W-23		W-4		W-35		W-30		W-27		W-41
f'_c (psi)	COV (%)	f'_c (psi)	COV (%)	f'_c (psi)	COV (%)	f'_c (psi)	COV (%)	f'_c (psi)	COV (%)	f'_c (psi)	COV (%)	f'_c (psi)	COV (%)	f'_c (psi)	COV (%)	f'_c (psi)
,570	0.6	7,240	3.0	8,070	4.5	7,640	2.0	8,520	0.1	8,070	2.1	8,190	1.2	7,900	0.2	8,620
,210	4.2	10,160	2.8	10,950	3.2	10,220	9.6	10,410	3.6	10,430	2.4	11,150	1.1	11,410	5.3	10,740
		10,370 (9,690)	2.9			9,760 (9,120)	1.0			11,090 (10,360)	3.1			10,390 (9,710)	3.3	9,490 (8,870)
,960 (,310)	1.9			9,060 (8,470)	0.4			9,150 (8,550)	1.9			9,320 (8,710)	4.6			

ks, 18 by 18 by 14 in.

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Used in Spheres

)V for---

·. 1		Sphere No. 10				Sphere No. 18				Average	
W-35		W-30		W-27		W-41		W-42			
f'_c (psi)	COV (%)	f'_c (psi)	COV (%)	f'_c (psi)	COV (%)	f'_c (psi)	COV (%)	f'_c (psi)	COV (%)	f'_c (psi)	COV (%)
8,070	2.1	8,190	1.2	7,900	0.2	8,620	2.3	7,970	2.1	8,000	5.3
										10,420	0.7
0,430	2.4									10,510	3.1
		11,150	1.1	11,410	5.3	10,740	7.8	11,080	1.3	11,090	2.5
										9,260	3.7
11,090 (10,360)	3.1									10,110	8.0
				10,390 (9,710)	3.3	9,490 (8,870)	3.2			9,940	4.2
										8,130	4.0
										9,120	7.4
		9,320 (8,710)	4.6					9,190 (8,590)	2.6	9,240	1.2

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Table 2b. Relative Compressive Strength Test Results for Test Specimens From Concrete Batches Used in Spheres

Item	Relative Strength Ratio[a] for-- Sphere No. 3		Sphere No. 11		Sphere No. 12		Sphere No. 13		Sphere No. 1		Sphere No. 10		Sphere No. 18		Average	
	W-15[b]	W-16	W-24	W-21	W-32	W-29	W-26	W-23	W-4	W-35	W-30	W-27	W-41	W-42	Ratio	COV[c] (%)
Continuous fog-cured specimens with age at test:																
1.3 yr	1.229	1.233													1.231	
5.6 yr			1.454	1.387	1.349	1.403	1.357	1.338	1.222	1.292					1.350	5.2
10.8 yr											1.361	1.444	1.246	1.390	1.360	6.1
On-land, field-exposed specimens with age at test:																
1.3 yr	1.087														1.087	
5.6 yr				1.192		1.432		1.277		1.374					1.319	8.0
10.8 yr												1.315	1.101		1.208	10.4
Ocean-exposed specimens with age at test:																
1.3 yr		0.968													0.968	
5.6 yr			1.103		1.316		1.123		1.074						1.154	9.5
10.8 yr											1.138			1.153	1.146	0.9

[a]Relative strength = $(f'_c)_T/(f'_c)_{28}$. Ratio of f'_c at given total age and exposure to f'_c at 28-day fog cure.
[b]Hemisphere identification number.
[c]Coefficient of Variation.

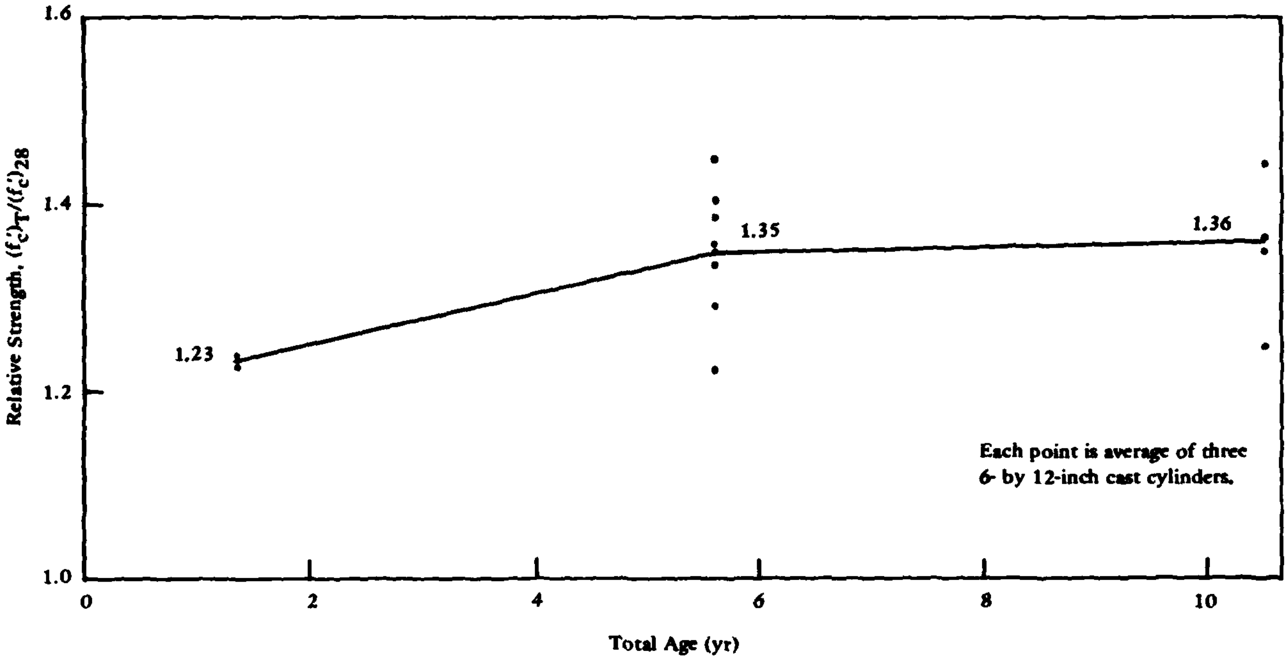


Figure 6. Relative compressive strength gain of concrete exposed to continuous fog cure.

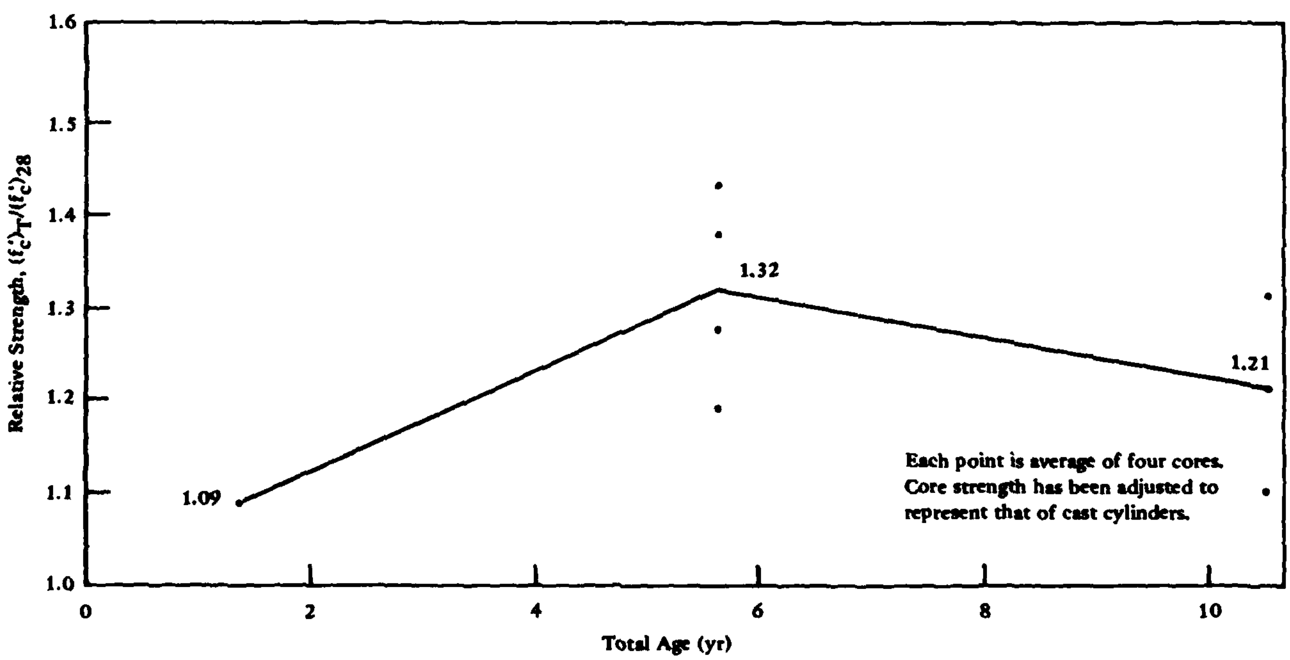


Figure 7. Relative compressive strength change of concrete exposed to on-land field conditions after initial 28-day moist cure. Location was about 150 ft from ocean.

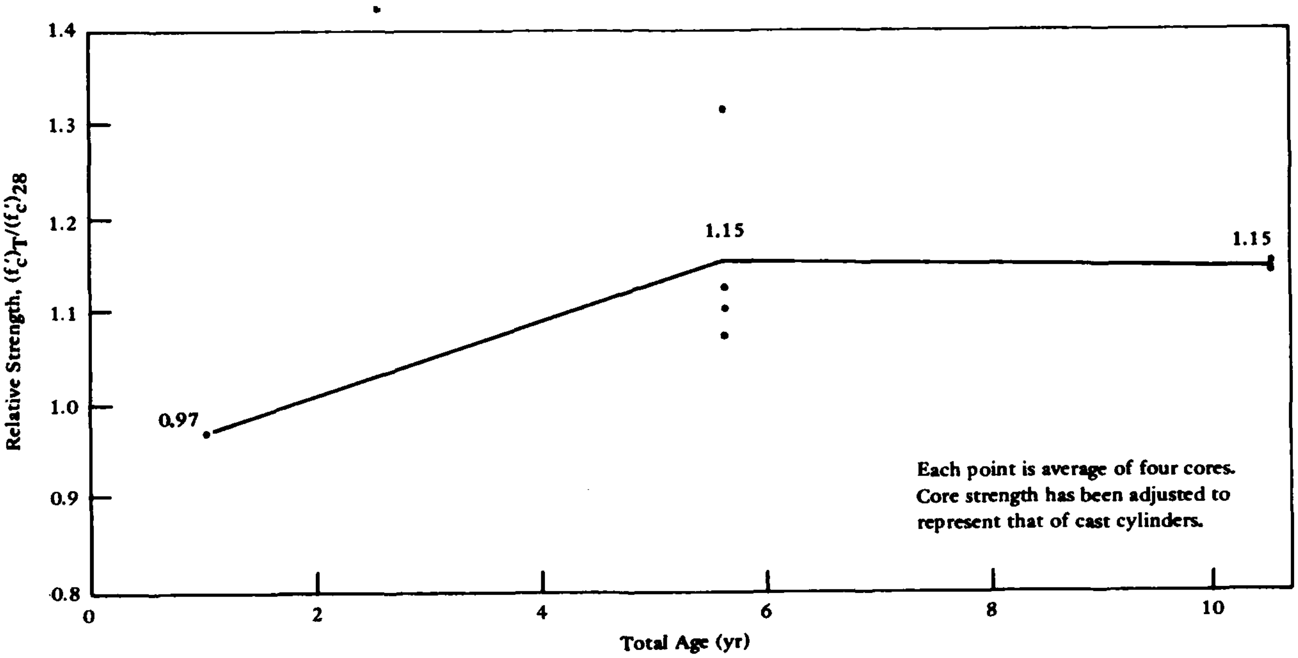


Figure 8. Relative compressive strength gain of concrete exposed to ocean conditions after initial 28-day moist-cure and 2 to 5 months of on-land field exposure.

Figure 9 is a summary comparison of the average relative strengths of the concrete exposed in the three environments. The strongest concrete at all ages was, as expected, continuously cured in a fog room, followed by the on-land and then the ocean-exposed concretes. The fog-cured concrete was, on the average, about 25% stronger than that exposed in the ocean for 1 year and averaged about 17% stronger than the ocean-exposed concrete at 5.6 and 10.8 years total age.

The finding that the strength of ocean-exposed concrete has been maintained at essentially the same level during the 5.6- to 10.8-year period may be used to support and extend the "Interim Guide" proposed in Reference 2 for predicting strength changes in saturated concrete in the ocean. The overall data to date indicate that for ocean-exposed concrete the strength increase relative to the 28-day, fog-cured strength appears to be zero at the end of 1 year, 5% at 2 years, and 15% at 5 to 10 years.

Figures 10 through 12 are stress-strain curves for the concrete cylinders tested after 10.8 years total age in accordance with ASTM C-469. Axial and lateral deformations were measured by a mechanical combined compressometer and extensometer. The curves contain data up to a nominal 40% compressive strength (f'_c) (3,870 psi).

The chord modulus of elasticity, E, and Poisson's ratio, ν, shown in Table 3 were calculated from the stress-strain curves between a point of small initial axial strain (nominally 50 μin./in.) and a point of nominal 40% f'_c. The modulus of elasticity of the continuously fog-cured specimens at 5,290,000 psi at 10.8 years age and 5,330,000 psi at 5.6 years was essentially constant for the past 5 years, and at both ages

Table 3. Summary of Modulus of Elasticity and Poisson's Ratio Data from Cylindrical Test Specimens

Type of Specimen	Curing and Early Environment	Dominant Exposure Environment	Total Age (yr)	Type of Cylinder	No. of Specimens	Average Elastic Modulus, E (10^6 psi)	Relative Elastic Modulus, $E/E_{fog\text{-}cured}$ (at a given age)	Average Poisson's Ratio, ν
Continuously Fog-Cured	100% relative humidity; 73°F	100% relative humidity; 73°F	5.6	Cast[a]	24	5.33	1.00	0.21
			10.8	Cast	12	5.29	1.00	0.19
On-land Outdoor Field Exposure	28-day moist cure (wrapped in wet burlap and plastic) then outdoor field exposure	Outdoors, 150 ft from shoreline	5.6	Cored[b]	16	4.21[c]	0.79	0.22
			10.8	Cored	8	4.27	0.81	0.16
Ocean Exposure	28-day moist cure (wrapped in wet burlap and plastic), then 3 to 5 mo outdoor field exposure	5.3 yr in ocean depths of 2,600 to 5,100 ft; 42°F	5.6	Cored	15	3.77	0.71	0.24
		10.5 yr in ocean depths of 1,840 to 3,200 ft; 42°F	10.8	Cored	7	4.04	0.76	0.20

[a] 6- by 12-in. cast cylinder.

[b] Nominal 6- by 12-in. cores drilled from cast blocks 18 by 18 by 14 in.

[c] Elastic modulus for cores determined from unadjusted data.

was significantly (25%) higher than the moduli of the on-land, atmosphere-exposed specimens, which in turn were about 8% higher than those of the ocean-exposed specimens. There were no systematic differences in the moduli between the 5.6- and 10.8-year specimens, nor was there a systematic difference between the saturated and the air-dried specimens.

Poisson's ratios, ν, which ranged from 0.16 to 0.24, are within the typical range of values for concrete in general; the ratios measured by mechanical compressometer at 10.8 years total age were systematically less than the ratios measured by strain gages at 5.6 years of age.

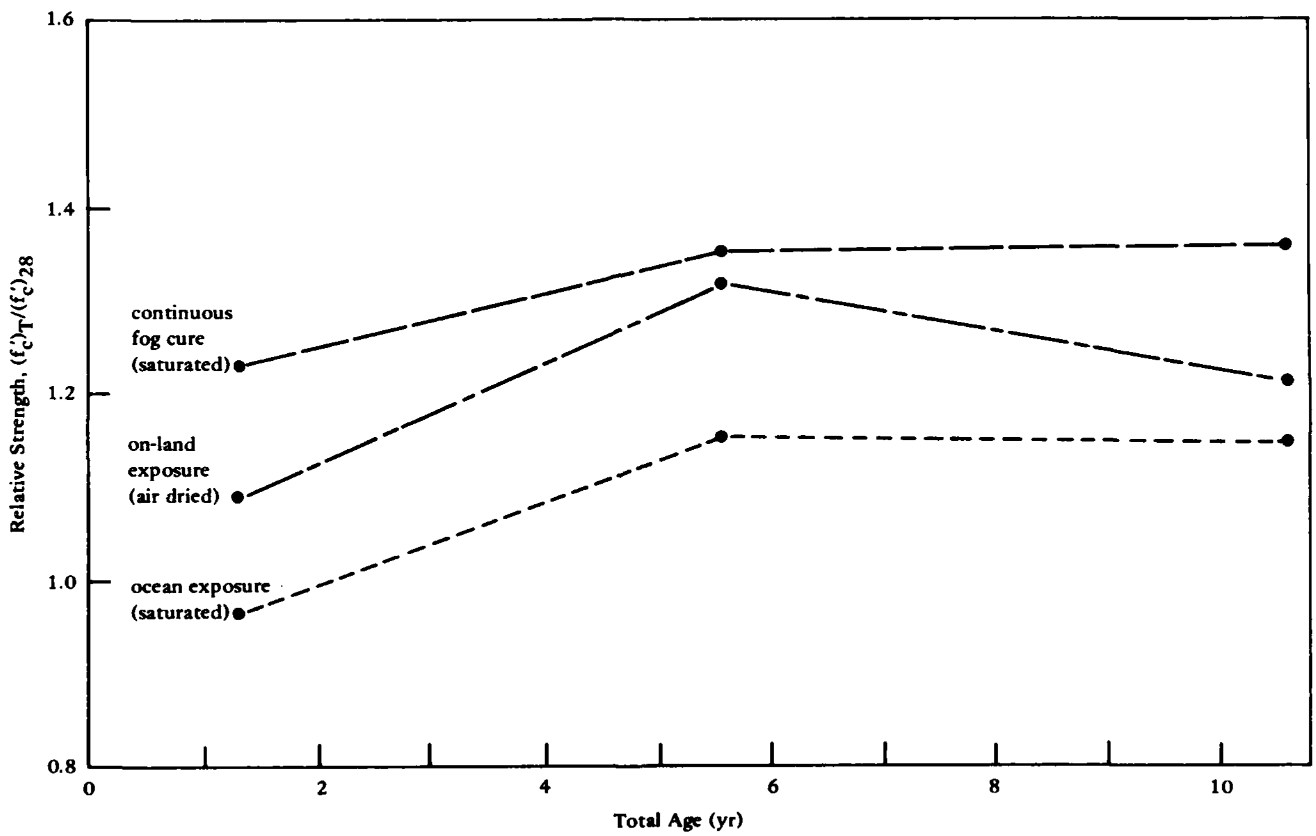


Figure 9. Average relative compressive strength changes of concrete in different environments.

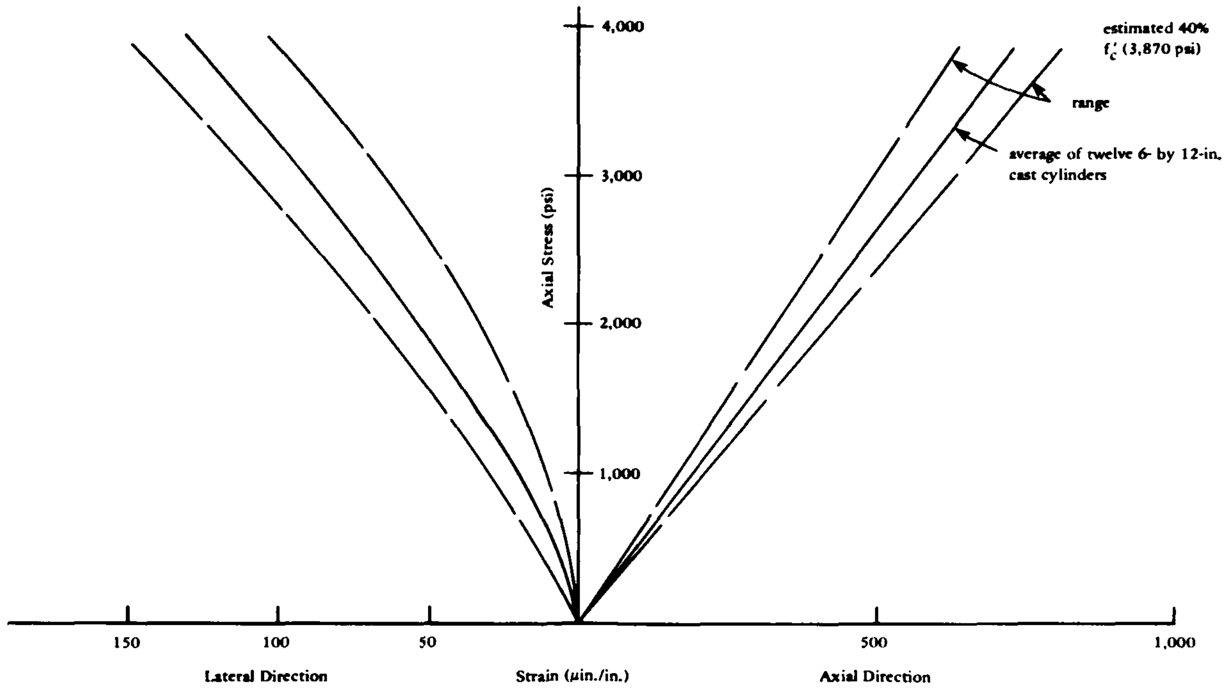


Figure 10. Uniaxial compressive strength tests of concrete continuously fog-cured for 10.8 years. Average compressive strength is 11,090 psi (range 10,000 to 12,100 psi).

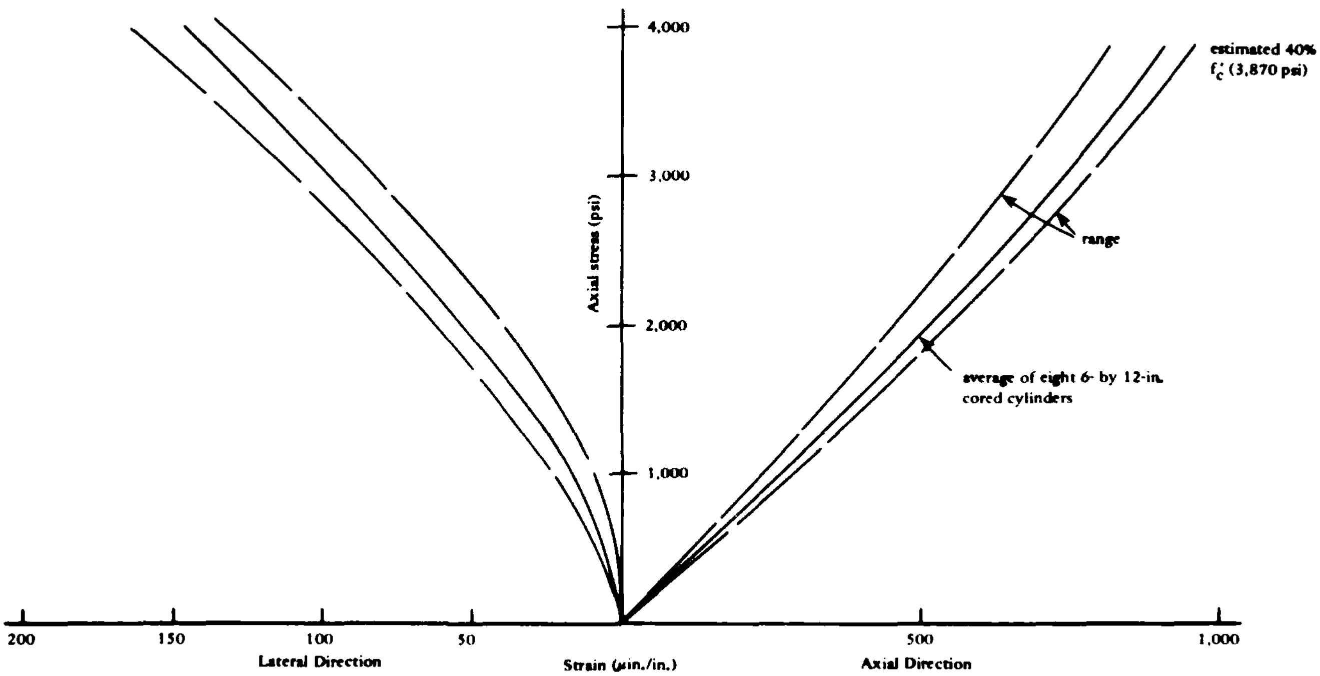


Figure 11. Uniaxial compressive strength tests of concrete field-exposed on land for 10.8 years. Average compressive strength is 9,940 psi (range 9,110 to 10,700 psi).

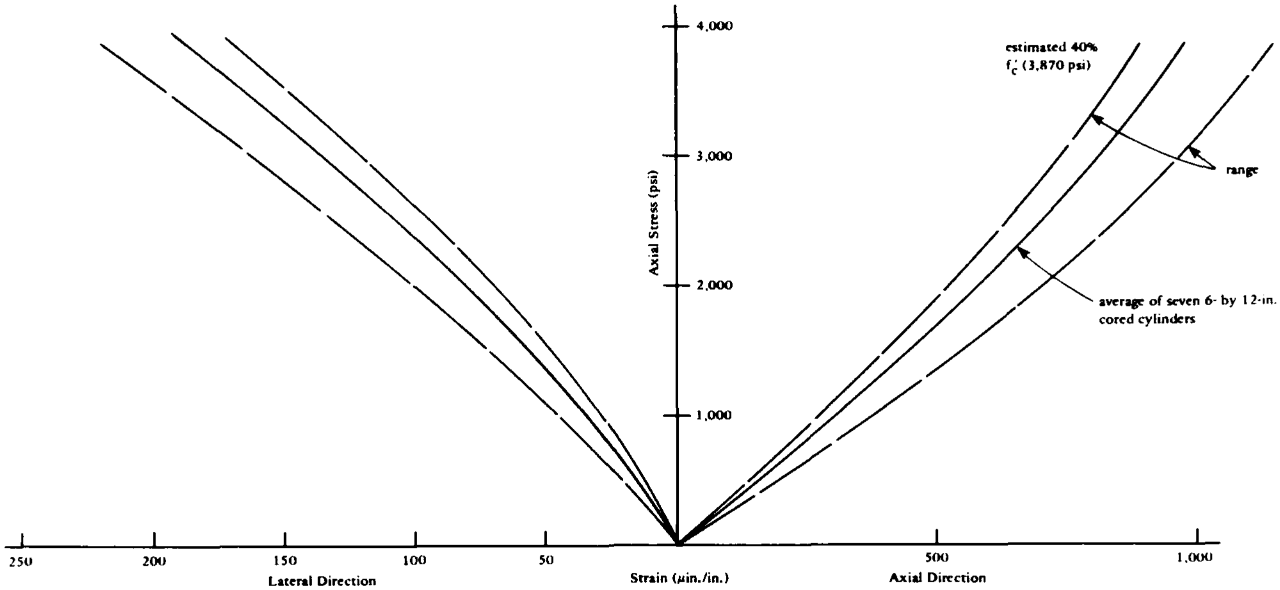


Figure 12. Uniaxial compressive strength tests of concrete exposed in the ocean for 10.5 years. Average compressive strength is 9,260 psi (range 8,870 to 9,800 psi).

Short-Term Loading of Spheres

Results at 10.8 Years of Age. The two spheres retrieved from ocean depths of 3,200 and 1,840 feet after 10.5 years in the ocean were tested to implosion failure under short-term loading by applying external hydrostatic pressure in a 72-inch-diam pressure vessel. As stated above, Sphere No. 10 was uncoated, and Sphere No. 18 had one coated and one uncoated hemisphere and was lightly reinforced with 1/2-inch steel rebar.

Each sphere was placed individually in the pressure vessel (Figure 13) and surrounded by seawater in which the pressure was then steadily increased at 50 psi/min until failure. Also, each sphere was filled on the inside with seawater which, however, was vented (through a penetration in the pressure vessel head) to atmospheric pressure. Thus, as the external pressure was increased, the sphere decreased in size and forced out some of its internal water, which was measured. This provided a direct measure of the decrease in internal volume of the sphere and, by calculation, the average biaxial hoop strain in the sphere wall. The average biaxial circumferential wall stress was calculated from the geometric ratio of the cross-sectional area of the 4.12-inch-thick sphere wall to the total 66-inch-diam sphere cross-sectional area. (The stress distribution across the sphere wall is probably not precisely uniform, as implied by this "average stress." However, because of the nonlinear stress-strain relationship of concrete, particularly near failure, the actual stress distribution is considered to be better

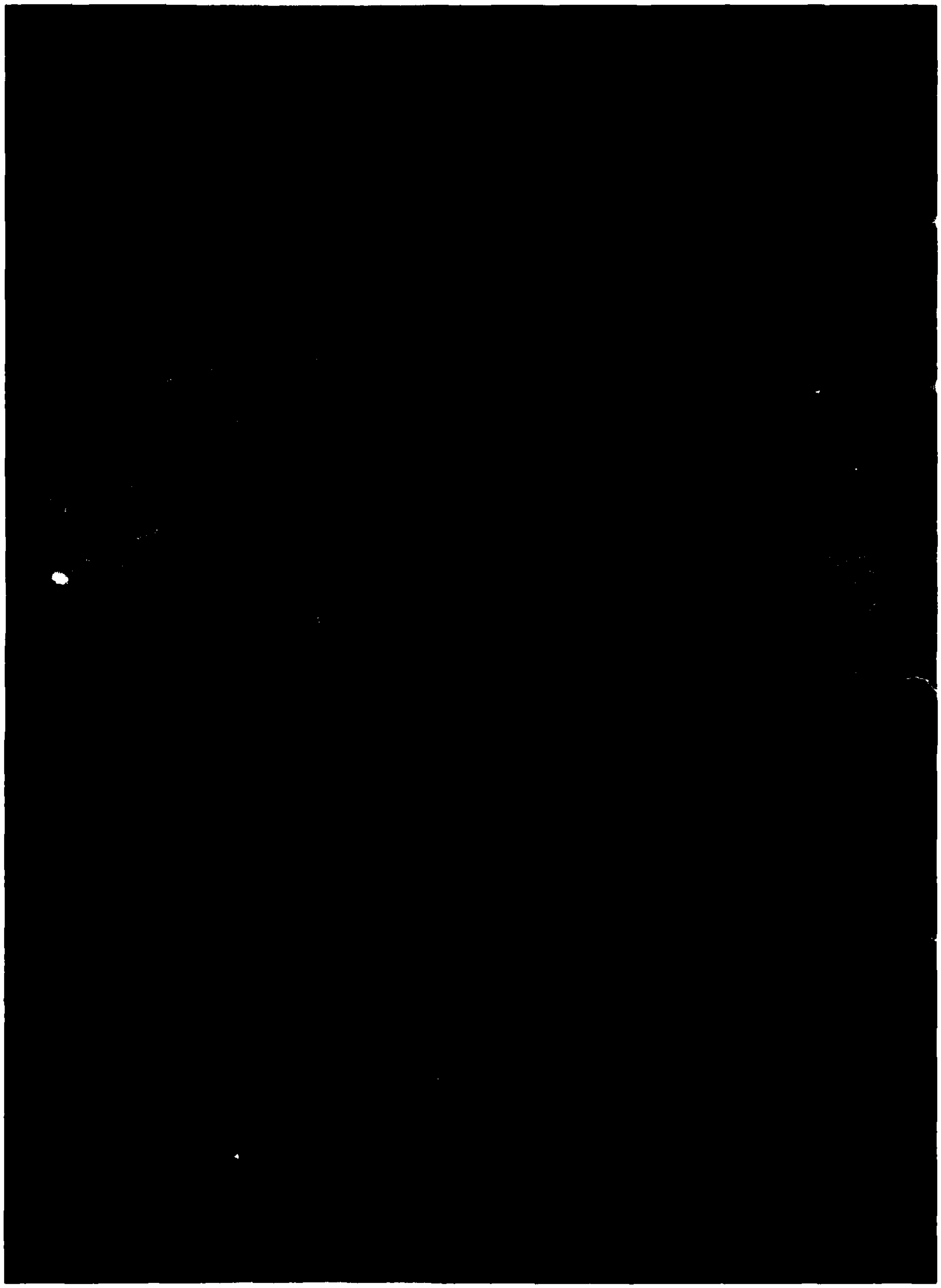


Figure 13. Sphere No. 18 being placed into pressure vessel.

represented by the assumed uniform stress than by the classic stress distribution across a thick-walled sphere of an ideally elastic material.) The measured load-deformation curves, with the calculated hoop stress and strain values for the two spheres, are shown in Figure 14.

Sphere Implosion Behavior. The concrete of Sphere No. 10 (which was uncoated and had, when recovered, free water on the inside) was assumed to be saturated; failure occurred in the upper hemisphere as shown in the postimplosion view in Figure 15. The lower half of Sphere No. 18 was also uncoated and saturated; failure occurred in this saturated lower hemisphere as seen in Figure 16.

The respective implosion (failure) loadings for Sphere No. 10 and 18 were very close together at 2,720 and 2,760 psi. While in the ocean, Sphere No. 10 had been subjected to 10.5 years loading of 52% of the implosion pressure, and Sphere No. 18 to 30%. Failure in both spheres was primarily in the compression-shear mode as shown in Figure 17. In addition, in Sphere No. 10 there was considerable in-wall delamination-type cracking "parallel to" (concentric to) and about 1 inch below the external surface, which led to exfoliation of various sized fragments up to 1 foot across, but all of very constant thickness; failure surfaces passed through (not around) coarse aggregate particles (Figures 18 and 19). These failure modes are essentially the same as those reported previously for preloaded spheres (Ref 2) and for nonpreloaded spheres (Ref 3). In Sphere No. 18 the small amount of reinforcing steel, which provided only very small amounts of additional area to resist either compressive hoop stresses or transverse (dowel action) shear stress, had little apparent effect on the ultimate strength or failure behavior of the sphere.

A minor type of local compressive failure (which did not participate in the overall structural failure of the sphere as a whole) consisted of small, circular (silver-dollar-size) spalls of concrete mortar that popped off at various locations scattered about the external surface of the spheres. The spalls were characteristically a shallow conical shape about 1/2 to 1 inch in diameter and 1/8 to 1/4 inch thick at the center, tapering radially to a feather edge. Some, but not all, of these small spalls were located concentrically over individual particles of coarse aggregate.

Sphere Strain Behavior. The short-term loading strain behavior of Sphere No. 10 and 18 is shown in Figure 14. The load-deflection curves are quite smooth to the point of failure; the curves diverge during the first quarter of the loading cycle, are approximately parallel for the next 50% of the range, and then converge as the failure point approaches. Thus, Sphere No. 18 is about 22% stiffer in terms of a chord modulus of elasticity (measured from an initial small load to 40% of the failure load) of 5.5×10^6 psi compared to 4.5×10^6 psi for Sphere No. 10. In the midloading range the spheres are about equally stiff, with tangential moduli of 5.1 to 5.3×10^6 psi. At failure the computed average maximum wall strains in the hoop direction (2,500 and 2,450 μin./in. for Sphere No. 10 and 18, respectively) and stresses (11,600 and 11,780 psi) are very close together, and the stress/strain ratios at implosion (4.6 and 4.8×10^6 psi) are within 4% of each other.

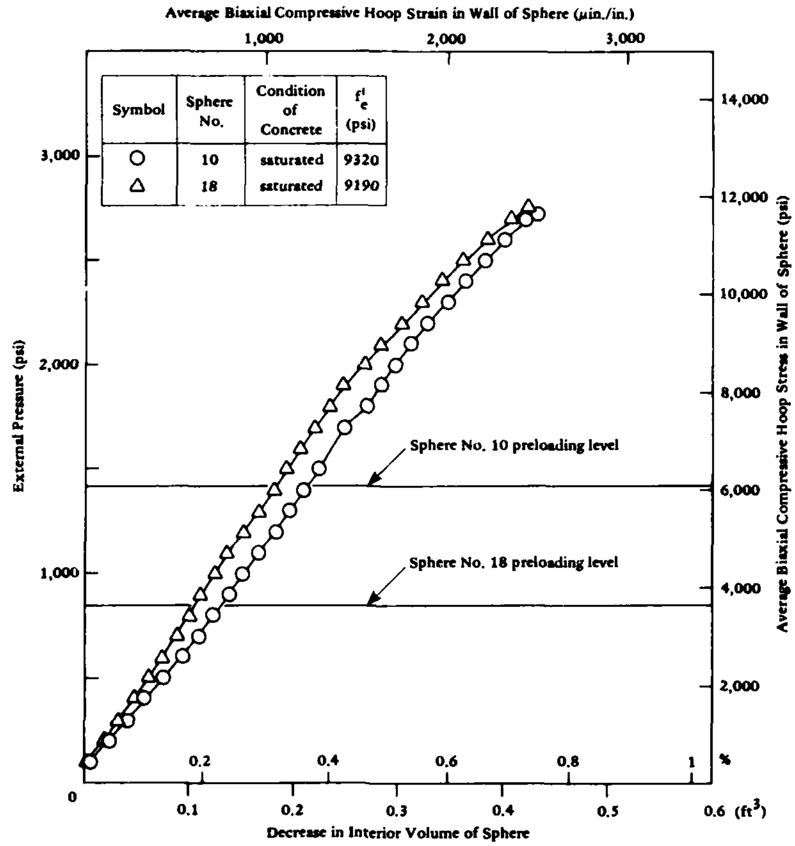


Figure 14. Short-term load/deformation behavior of concrete spheres preloaded 10.5 years.

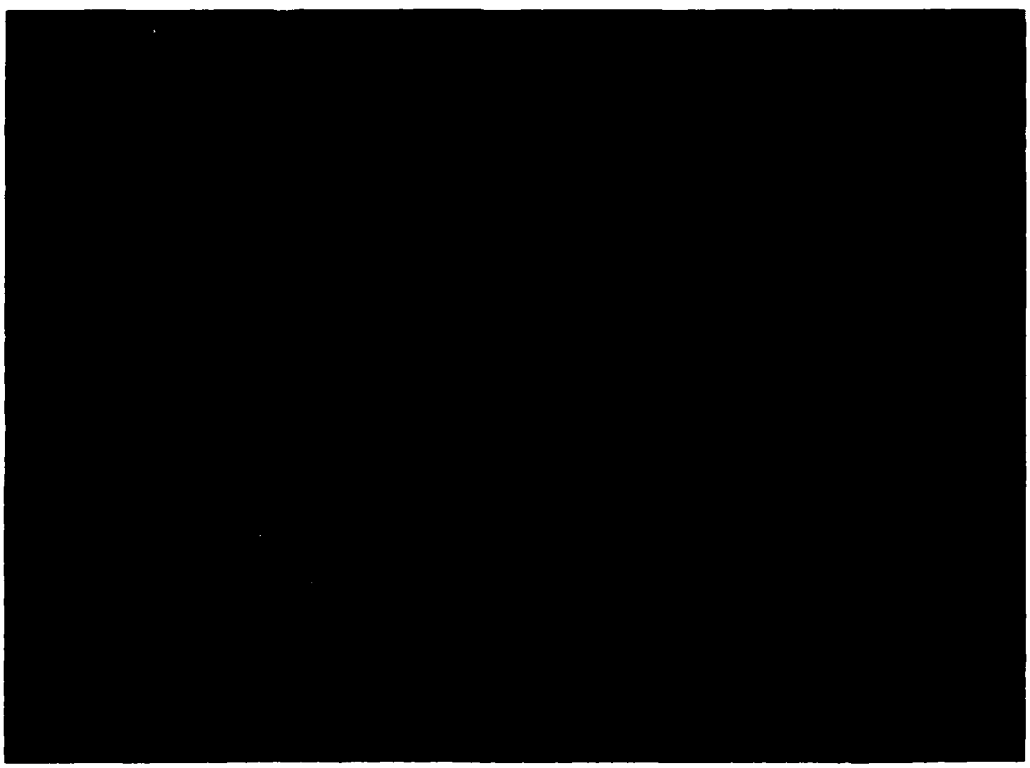


Figure 15. Postimplosion view of Sphere No. 10.

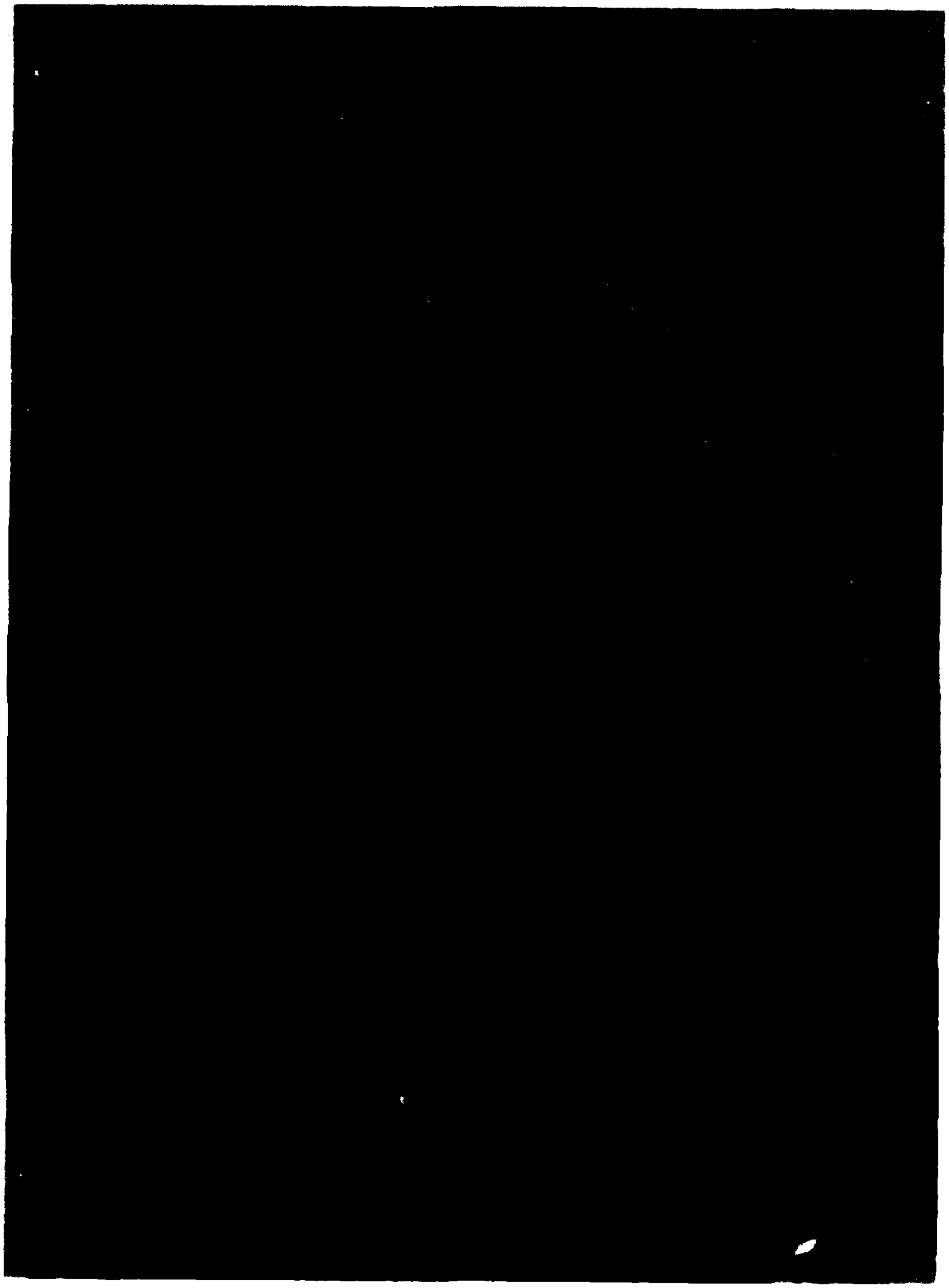


Figure 16. Postimplosion view of Sphere No. 18.

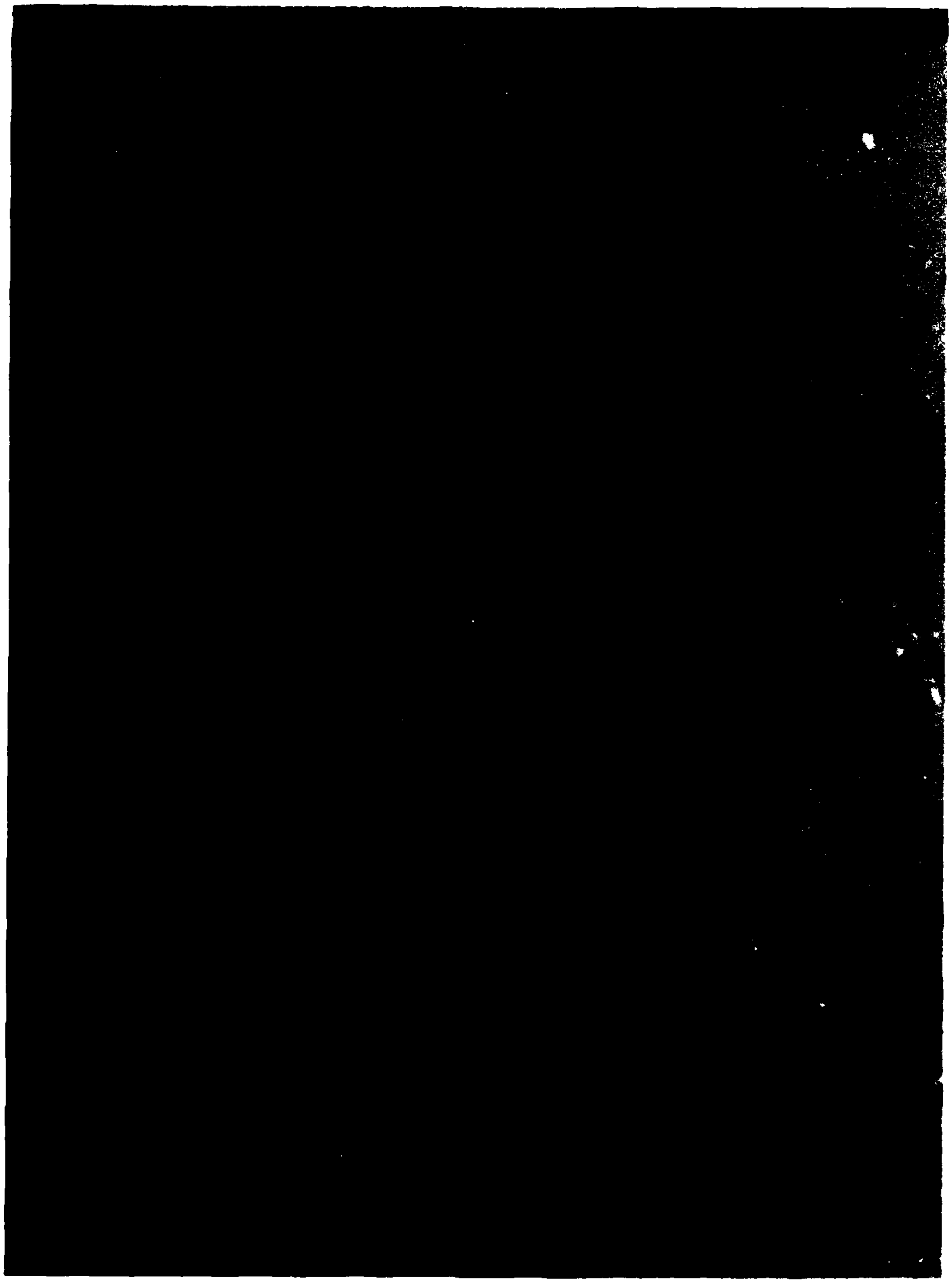


Figure 17. Compression-shear failure.

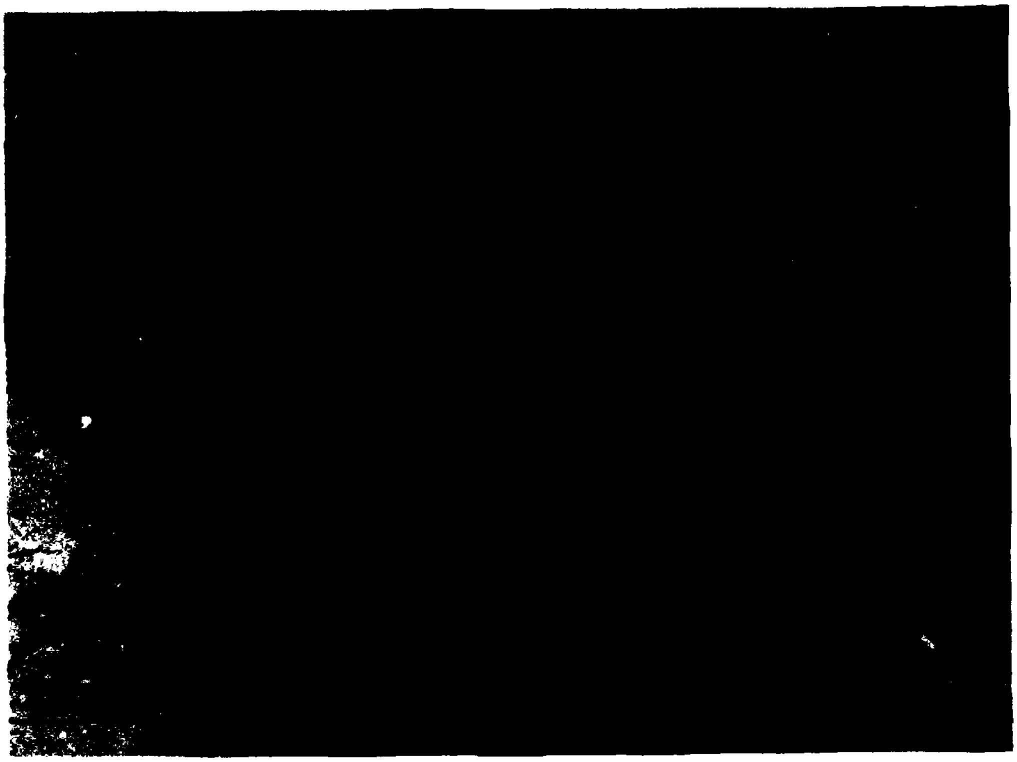


Figure 18. In-plane cracking failure (overall view).

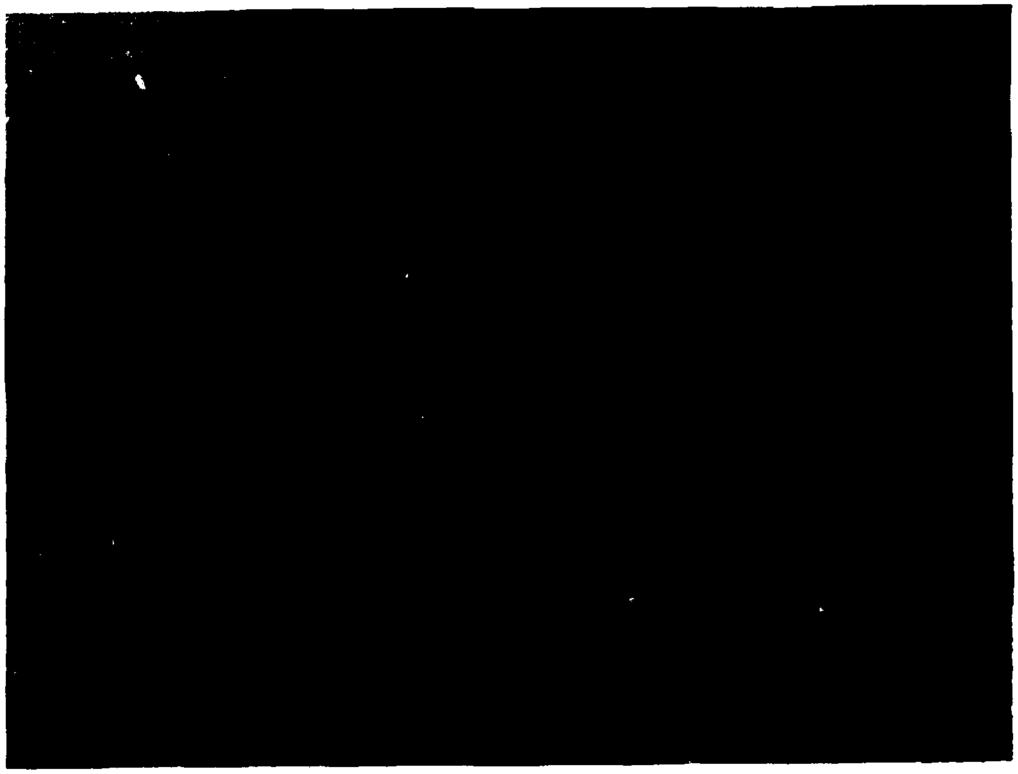


Figure 19. In-plane cracking failure (detail).

Comparative Overall Results. Results of the short-term loading tests of all five spheres recovered from the ocean to date after 5.3 or 10.5 years of sustained continuous preloading at ocean pressures of 30 to 52% of their implosion strengths are shown in Table 4 along with test results for four replicate spheres which, under a previous program, had been tested to implosion under short-term (pressure vessel) loading at a younger age (4 to 7 months) without first being subjected to sustained long-term loading (Ref 3). Averaged results are summarized in Table 5. Load-deformation curves for the five preloaded spheres and three of the nonpreloaded spheres are shown in Figure 20. Several trends are evident. The strength at failure by implosion will be discussed first.

Implosion Strength Behavior. The implosion failure strength of the "dry" (waterproofing-coated, partially saturated) spheres was significantly greater than that of the "wet" (saturated) spheres for comparable ages and loading condition (e.g., by 19% for the younger nonpreloaded spheres and 11% for the mature preloaded spheres). This is consistent with generally known information that a given concrete is stronger when tested in a dry (partially saturated) condition than when tested in a saturated condition.

The preloaded spheres are stronger at failure than the nonpreloaded spheres, by 8% for dry and 17% for wet spheres after 5.3 years preloading, and still the same (17%) for the wet spheres after 10.5 years. These gains can be directly attributed to the in-ocean strength increase with age of the ocean spheres, and closely parallel the pattern of strength changes of the uniaxial compressive strength specimens, which had gained strength after 5.3 years in the ocean and then leveled off and maintained that strength during the second 5-year period.

A useful parameter for strength comparisons is the nondimensional ratio P_{im}/f'_c (i.e., the ratio of the implosion pressure to the uniaxial compressive strength of cylinders made from the same batch of concrete and tested at the same age and the same wet or dry condition). This ratio is higher in all cases except one (Sphere No. CWS-3) for the dry (partially saturated) concrete as compared to saturated concrete (see Table 4); when the values at a given age are averaged, the average values for the dry concrete are consistently higher (Table 5).

There is no particular pattern of changes of the ratio P_{im}/f'_c with time, with both small increases and decreases at the nominal 5-year increments of age difference. Neither is there any evident correlation between changes in the ratio and the level of preloading (up to 52%).

All of these changes are small, with the P_{im}/f'_c ratio ranging from 0.28 to 0.31 for the wet concrete and 0.30 to 0.32 for the dry concrete. The important findings here are that the overall effect of preloading the spheres at stress levels of up to 50% of the ultimate strength for 10.5 years is small and, in particular, that to date there has not been any pattern of weakening due to the ocean exposure. Within the usual tolerance range of design specifications, the P_{im}/f'_c ratio determined from short-term loading can be used to predict the long-term performance of concrete spheres.

Table 4. Short-Term Loading Results of Concrete Spheres

Sphere Designation	Concrete Condition[a]	Time in Ocean (yr)	Sustained Preload Pressure, P_s (psi)	Short-Term Implosion Pressure, P_{im} (psi)	Ratio P_s/P_{im}	Uniaxial Compressive Strength, f'_c (psi)	Ratio P_{im}/f'_c	Elastic Modulus[b] of Sphere Wall, E (psi x 10^6)
10	saturated	10.5	1,420	2,720	0.52	9,320[c]	0.292	4.53
18[d]	saturated	10.5	820	2,760	0.30	9,190[c]	0.300	5.54
11[e]	dry	5.3	1,400	2,970	0.47	9,200[f]	0.323	5.05
12[e]	saturated	5.3	1,245	2,750	0.45	9,960[c]	0.276	5.07
13[e]	dry	5.3	1,175	3,115	0.38	9,760[f]	0.319	5.20
CDS-1[g]	dry	0	0	2,860	0	9,250	0.309	4.64
CDS-2[g]	dry	0	0	2,755	0	9,120	0.302	4.14
CWS-3[g]	saturated	0	0	2,500	0	7,960	0.314	--
CWS-4[g]	saturated	0	0	2,205	0	7,660	0.288	4.29

[a]Dry concrete corresponds to coated spheres; saturated concrete corresponds to uncoated spheres.

[b]At 40% of P_{im}.

[c]Nominal 6- by 12-in. cylinders cored from ocean-exposed blocks.

[d]Sphere No. 18 was half coated and half uncoated. Failure occurred in the lower uncoated hemisphere.

[e]Data are from Reference 2.

[f]Nominal 6- by 12-in. cylinders cored from on-land, field-exposed blocks.

[g]Data are from Reference 3.

Table 5. Summary of Short-Term[a] Loading Results for Concrete Spheres

Preloading Condition	Coated Spheres (Dry Concrete)	Uncoated Spheres (Saturated Concrete)
a. Average Implosion Pressure, P_{im} (psi)		
Preloaded 10.5 yr[b]	--	2,740
Preloaded 5.3 yr[b,c]	3,040	2,750
Nonpreloaded[d]	2,810	2,350
b. Average Ratio of Implosion Pressure to Compressive Strength, P_{im}/f'_c		
Preloaded 10.5 yr	--	0.296
Preloaded 5.3 yr	0.321	0.276
Nonpreloaded	0.306	0.301
c. Average Ratio of Moduli of Elasticity of Preloaded Spheres to Nonpreloaded Spheres		
Preloaded 10.5 years	----	1.17
Preloaded 5.3 years	1.17	1.18
Nonpreloaded	1.00	1.00

[a]Spheres loaded to failure in a pressure vessel.

[b]Preloading by ocean emplacement.

[c]Reference 2.

[d]Reference 3.

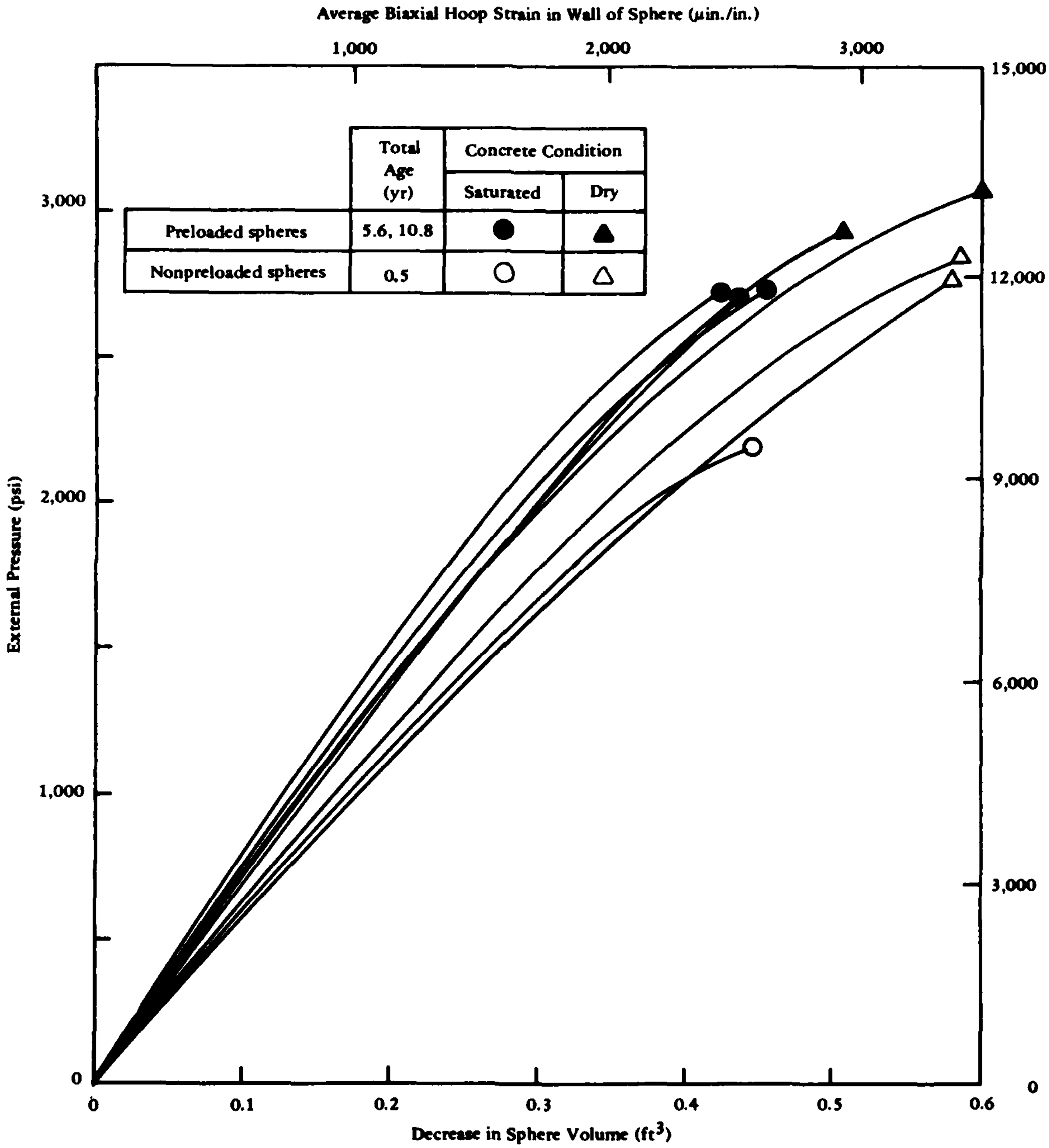


Figure 20. Load-deformation curves of preloaded and nonpreloaded spheres (Sphere No. 10, 18, 11, 12, 13, CDS-1, CDS-2, and CWS-4).

The failure mode of each of the spheres was primarily in the compression-shear pattern, typically along a several-foot-long arc, with an angle of breaking of 30 to 40 degrees from a tangent to the interior surface of the sphere. In most failures this was followed by secondary cracks at right angles to the surface due to hinge action (bending) as one or more large segments of the sphere moved inward.

The most noteworthy of the "in-plane" (concentric layer delamination) type secondary failures occurred in wet (saturated) spheres (e.g., Sphere No. 10, cited above, and in Sphere No. CWL-5 and CWL-9 of Reference 3). However, not all wet spheres displayed evident delamination cracking. The nine spheres discussed so far in this section all had an outside diameter, D_o, of 66 inches and a wall thickness, t, of 4.12 inches (i.e., with t/D_o ratios of 0.0625). Reference 3 includes discussion of tests on the behavior of 16-inch-diam spheres with t/D_o ratios ranging from 0.0625 to 0.25 in which in-plane cracking occurred in those spheres with t/D_o ratios of 0.125 and greater.

Sphere Strain Behavior. The dry spheres in all cases deflected more before failure than the wet spheres, with average dry sphere failure strains (3,300 μin./in.) 30% greater than the average failure strains (2,540 μin./in.) of the wet spheres. On the other hand, there was little change in failure strain with age or amount or length of time of preloading. For the wet spheres each of the individual failure strains for the various preloading conditions was within 4% of the overall average. More individual scatter occurred with the dry sphere failure strains, but again the average values at 5.3 years preloading were within 4% of the average values of nonpreloaded spheres. These data support the concept of using a limiting strain criterion as a design guideline.

The preloaded spheres were consistently stiffer than the nonpreloaded spheres. The average chord moduli of elasticity (measured from a low initial strain level to about 40% of the failure load) averaged about 17% greater for both dry and wet preloaded spheres, as shown in Table 5 and graphically in Figure 20. Also from Figure 20 it is apparent that the stress/strain ratio at failure is significantly higher for the preloaded spheres. This greater stiffness can be attributed to the higher strengths of the older preloaded spheres. Also, sustained long-term preloading and resultant creep may have contributed to the increased stiffness as discussed in Reference 2. There do not appear to be other significant differences in stiffness (e.g., for the preloaded spheres as a group the moduli are similar for both wet and dry spheres and for both 5.3 and 10.5 years of preloading).

Long-Term Loading of Spheres

Of the original 18 spheres, 3 have imploded in the ocean. Sphere No. 3 failed during its free-fall descent before it reached the seafloor at 4,300 feet during the original deployment. Sphere No. 1 at 5,075 feet and Sphere No. 7 at 3,725 feet imploded in situ. They were first inspected at 3 and 1.2 years, respectively, after deployment. Therefore, they are assumed to have failed either at initial touchdown or sometime during the period before the first inspection.

Two spheres leaked but did not implode. Sphere No. 8 at 3,665 feet was found lying intact on the seafloor at the time of its initial inspection in 1972. There was no externally visible damage; it is assumed to have leaked at the time of its deployment or during the first 1.3 years that it was in the ocean. Sphere No. 4 at 4,185 feet was inspected four times during its first 9.6 years in the ocean and, in each case, was found to be floating off the seafloor with a consistent chain link count. However, on its fifth inspection in November 1984, it was found to be flooded and lying on the seafloor. It had not imploded, but sometime during the 3-1/2 years since its previous inspection, it had failed locally near the top of the sphere where there is a small (about 4-inch-diam) hole. This failure may be related to a through-wall penetration at the upper pole of the sphere; a specific determination of the failure mechanism will require additional in-situ inspection or retrieval of the sphere for first-hand observation. This is the first instance to date of this mode of failure of any of the spheres exposed in the ocean or tested in the laboratory.

One sphere (No. 6) has never been inspected. None of the other 12 spheres have imploded in the ocean. These spheres (which include the five spheres retrieved from the ocean for the on-land laboratory tests described above) continued to gain strength in place for several years. Thus, the relative load levels, P_s/P^p_{im} (i.e., the ratio of the sustained pressure in the ocean to the predicted short-term failure loads), decreased during that time, and the spheres became less likely to fail by implosion.

Since both the in-ocean and reference fog-cured concretes had essentially *no change in strength* between 5.6 and 10.8 years of age, the information on long-term loading (with the exception of Sphere No. 4 as described above) presented in Figures 21 and 22 and Table 6 of Reference 2 is still considered to be current.

Seven intact spheres remain floating in the ocean just above the seafloor in water depths ranging from 1,980 to 4,875 feet with relative load levels of 0.33 to 0.68.

Permeability

Water taken on by the spheres in the ocean can be considered to consist of two portions: water that is absorbed by the concrete, and water than permeates through the concrete after it has become saturated.

The spheres, after their initial 28-day moist cure and prior to their ocean deployment, had been exposed to the atmosphere for varying lengths of time (3 to 21 weeks) and thus were in an air-dried condition with various moisture contents at the time they were placed in the ocean. In previous evaluations (Ref 1 and 2) it was assumed that the concrete in this air-dried (partially saturated) condition contained, on the average, 3% by weight of pore water (7% by volume) and it was estimated that the concrete could absorb an additional 3% by weight of water before becoming fully saturated. The weight of concrete in each sphere is about 4,160 pounds, so the absorption would be about 125 pounds or an estimated 2.0 ft^3 of water. For the present analysis this has been adjusted to an estimated 2.5 ft^3 additional absorption based on an average moisture determination of 6.8% for the ocean-exposed blocks for Sphere No. 10 and 18 and 6.3% for fog-cured concrete (all assumed to be saturated), continuing to assume an average 3% moisture content of the air-dried spheres at their time of deployment in the ocean.

Table 6. Apparent Water Intake of Spheres in Ocean

Parameter	Years in Ocean	Coated Spheres				Uncoated Spheres						Half-coated Spheres	
		No. 2	No. 11	No. 13	No. 14	No. 4	No. 5	No. 10	No. 12	No. 15	No. 16	No. 17	No. 18
Assumed Chain Link Count at Start of Test		29.7	34.0	32.1	43	29.4	29.6	31.6	31.7	32.2	31.8	32.6	32.6
Chain Size (in.)		2-1/4	2-1/8	2-1/4	2	2-1/4	2-1/4	2-1/4	2-1/4	2-1/4	2-1/4	2-1/8	2-1/8
Cumulative Change in Chain Link Count[a], ΣΔL, for													
Inspection 1	0.45			4.1	4.0					6.2	5.8	3.6	
Inspection 2	0.93					6.4	8.6						
Inspection 3	1.2		3.0	4.1	4.0			7.6	7.7	7.2	6.8	4.6	7.6
Inspection 4	2.1		3.0	3.1	4.5			7.6	7.2	6.7	6.8		
Inspection 5	3.1			3.1	4.8				7.2	6.5	7.8	3.6	
Inspection 6	5.3	2.7	3.5	3.1	5.0	7.4	11.6	8.6	7.2	7.2	8.8		b
Inspection 7	6.5									6.5	9.8	3.6	
Inspection 8	8.5									b	9.8	4.6	7.6
Inspection 9	9.6	2.7			5.0	8.4	11.6			7.2		3.6	
Inspection 10	10.5							9.6		8.5	8.6	4.4	b
Inspection 11	11.1				4.3					8.7	9.3	4.1	
Inspection 12	13.1	2.7				e	12.1			8.5	9.8		
ΔLinks - From Deployment to Initial Inspection		2.7	3.0	4.1	4.0	6.4	8.6	7.6	7.7	6.2	5.8	3.6	7.6
ΔLinks - From Initial to Most Recent Inspection		0	0.5	-1.0	0.3	2.0	3.5	2.0	-0.5	2.3	4.0	0.5	0
ΔLinks - From Deployment to Most Recent Inspection		2.7	3.5	3.1	4.3	8.4	12.1	9.6	7.2	8.5	9.8	4.1	7.6
Water Quantity per Link (ft^3)		0.488	0.406	0.488	0.325	0.488	0.488	0.488	0.488	0.488	0.488	0.406	0.406
Apparent Total Water Gain[c] (ft^3)		1.32	1.42	1.51	1.40	4.10	5.90	4.68	3.51	4.15	4.78	1.67	3.09
Absorbed Water (Assumed) (ft^3)		1.32	1.42	1.51	1.40	2.50	2.50	2.50	2.50	2.50	2.50	1.67	2.50
Permeated Water (Inferred) (ft^3)		0	0	0	0	1.60	3.40	2.18	1.01	1.65	2.28	0	0.59
Permeated Water (Measured)[d] (ft^3)			0	0				1.91	1.24				0.37

[a]The precision of the chain link count is considered to be ±1 link.

[b]Chain link counts for these observations appear to be in error and are not included in the calculations (see discussion in text).

[c]From time of deployment to most recent inspection.

[d]Water found inside the spheres retrieved from the ocean.

[e]Sphere observed lying on seafloor with small hole in top; permeation data are for the initial 9.6-year period.

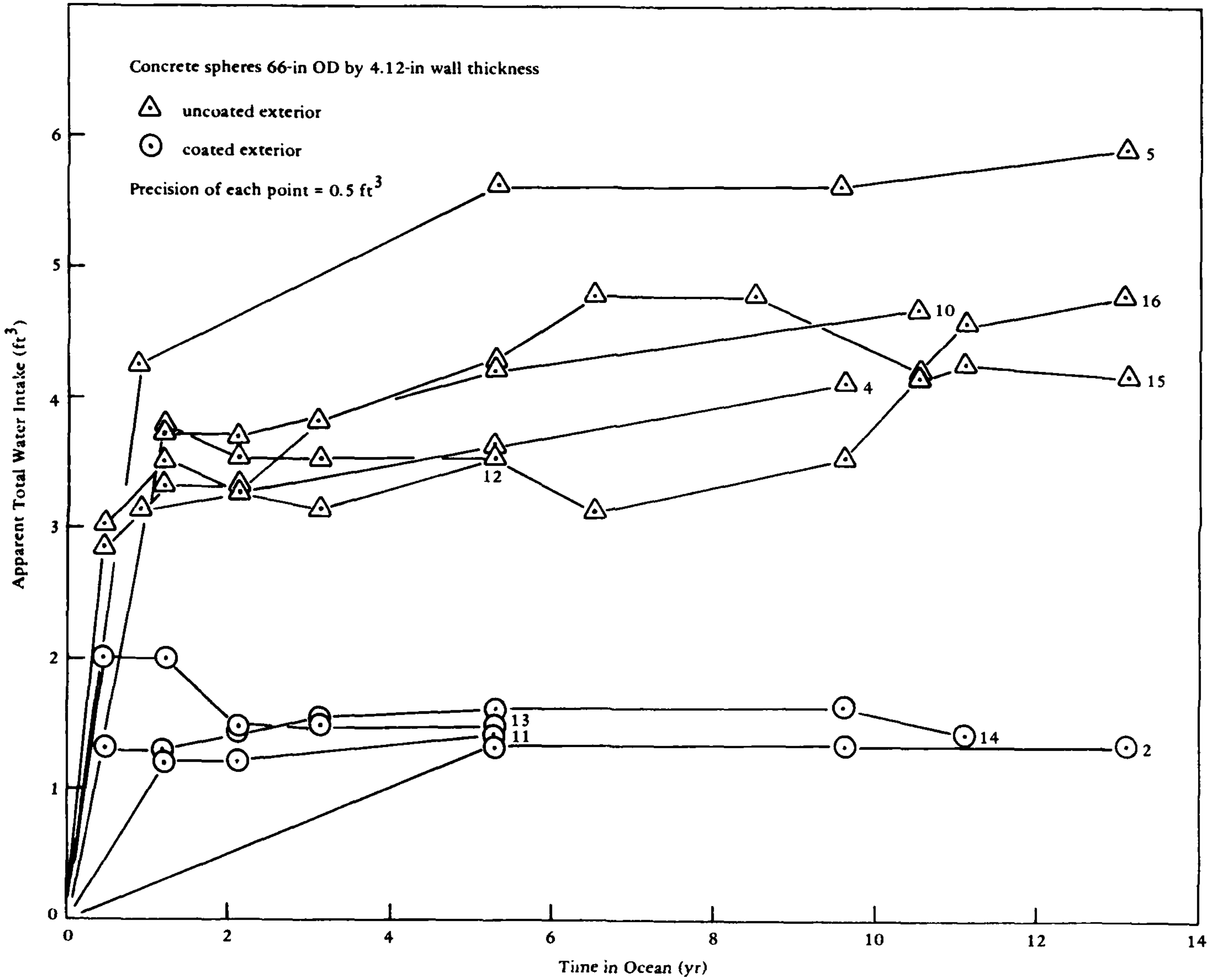
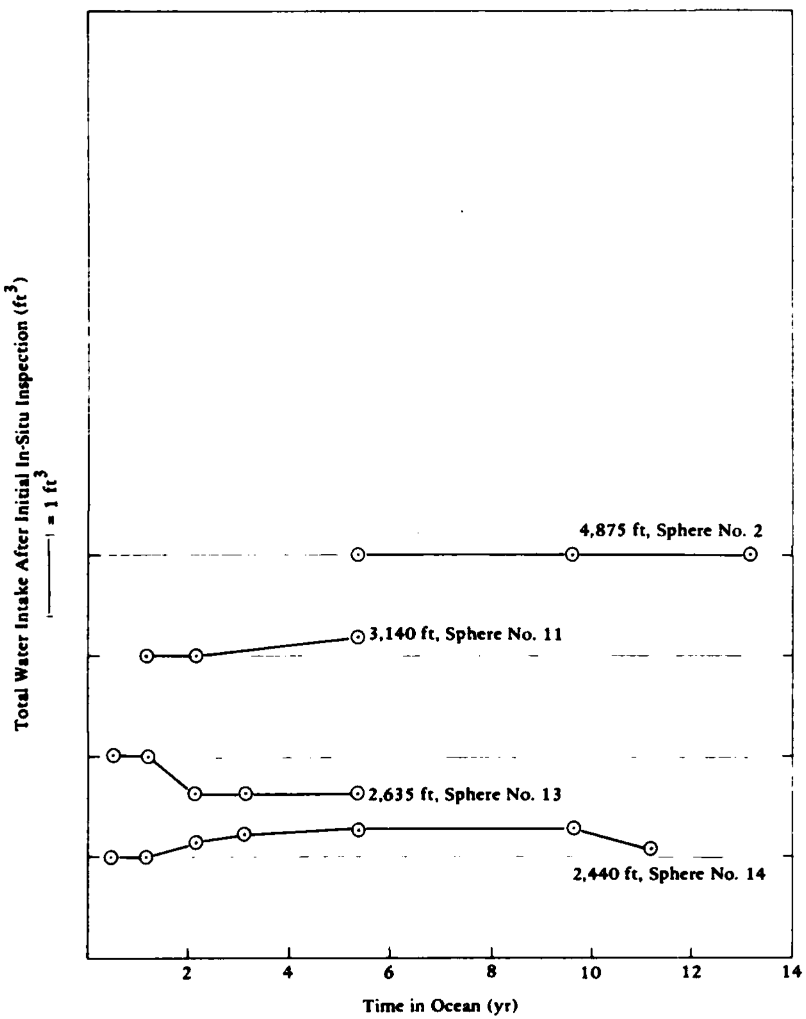
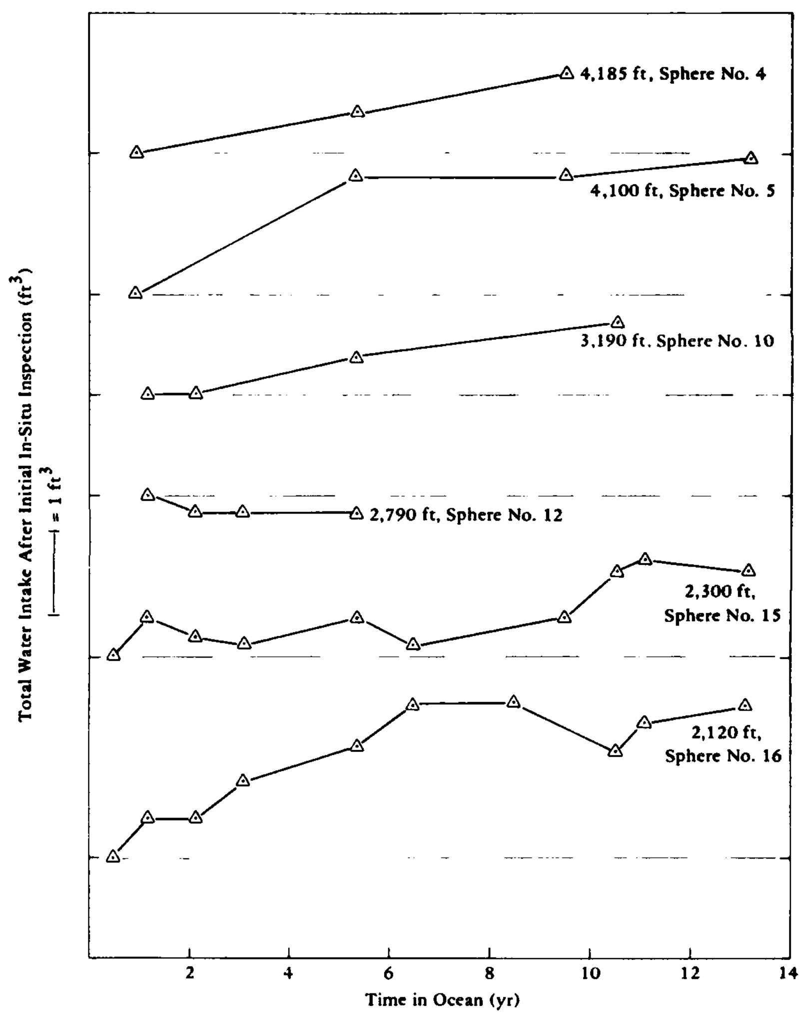


Figure 21. Apparent total water intake for spheres in the ocean for extended periods.



(a) Coated spheres.



(b) Uncoated spheres.

Figure 22. Changes in apparent water intake after first in-situ inspection.

Table 1 lists the number of chain links suspended off the seafloor by the spheres as reported during the various inspections. Table 6 lists the changes in the chain link counts and presents the assumed intake of water based on the in-water weight of the chain. Of particular interest are: (1) the change in the number of links between the assumed number of links at the time of deployment and the actual count at the time of the first inspection, and (2) the changes in chain link counts after the initial inspection. The changes are caused by a loss of buoyancy due to weight gain from water absorption and permeability. The assumed chain link counts at the start of the test are theoretical values calculated from known weights of the sphere assembly components (Ref 1).

Figure 21 is a comparison of time in the ocean to apparent total water intake as estimated from the chain link counts. The general trend is a rapid initial intake of water followed by a gradual increase by the uncoated spheres but no further intake of water by the coated spheres.

Figure 22 shows the apparent changes in total water intake for individual spheres after their initial in-situ inspections (which varied from less than one-half to greater than 5 years after deployment in the ocean). Chain link counts for coated spheres did not vary more than one link (least count is ±1 link); thus, it is shown that none of the coated spheres took on any significant amount of water after the initial inspections as seen in Figure 22a. The chain link counts for individual uncoated spheres (Figure 22b) show some variations within the precision of counting (±1 chain link), but, as seen particularly in the curve for the overall average, there is a general trend to continue taking on small amounts of water throughout the 12-year period represented by the data.

The uncoated sphere (No. 10) retrieved in March 1982 followed the general trend. It was first inspected 1.2 years after emplacement. Its calculated permeated water was 1.2 ft^3 (in addition to 2.5 ft^3 of absorbed water). Inspection 1 year later indicated the same amount of water with an increase of an additional 1/2 ft^3 at each of two later inspections so that the estimated amount of water inside the sphere after 10.5 years in the ocean was 2.2 ft^3. The measured amount of free water found inside the sphere after it had been retrieved from the ocean was 1.91 ft^3. The previously retrieved (after 5.3 years in the ocean) uncoated Sphere No. 12 contained 1.24 ft^3 of permeated water. The estimated amount of water, based on the chain link counts and assuming 2.5 ft^3 of absorbed water, was 1.0 ft^3. The other sphere (No. 18) retrieved in March 1982 had one coated hemisphere and one uncoated hemisphere. The chain link inspections indicated 0.6 ft^3 of permeated water after 1.2 and 8.5 years. The actual directly measured amount of free water found in the sphere after it was retrieved was 0.37 ft^3. These close estimates of permeated water give support to the chain link counts and the assumptions regarding absorbed water.

Of the five spheres recovered from the ocean to date, two were coated on the outside with the waterproofing material. After 5.3 years in the ocean neither of these contained any free water on the inside (Ref 2). As stated above, the uncoated sphere recovered after 5.3 years contained 1.24 ft^3 of water on the inside (Ref 2); the uncoated Sphere No. 10 and the half-coated Sphere No. 18 retrieved after 10.5 years

submergence contained 1.91 and 0.37 ft^3 of permeated water, respectively. Thus, the plain uncoated concrete was not "perfectly watertight," but these values represent very small quantities of water. In Sphere No. 10 the water that has permeated the 4-1/8-inch-thick concrete in over 10.5 years time at a pressure head of 1,420 psi represents about 3% of the interior volume of the sphere.

D'Arcy's coefficient of permeability may be expressed as:

$$K_c = \frac{Q_p\ t}{T\ A\ h}$$

where:
K_c = permeability coefficient, ft/sec

Q_p = quantity of permeated water, ft^3

t = wall thickness, ft

T = time, sec

A = interior surface area of sphere, ft^2

h = pressure head, ft

D'Arcy's theory assumes that K_c is constant with time, which is not the case for permeation of water into the spheres. However, if an average permeation rate is assumed, then the secant permeability coefficients calculated for the three water-containing spheres (with differing pressure heads, time in ocean, and overall area) are reasonably consistent ranging from 0.6×10^{-14} to 1.2×10^{-14} ft/sec as shown in Table 7. They also are consistent with findings by Powers et al. (Ref 4) of K_c ranging from 0.3×10^{-14} to 400×10^{-14} ft/sec for cement pastes with water/cement ratios of 0.3 to 0.7 and a K_c of 3.3×10^{-14} ft/sec for a cement paste with a water/cement ratio of 0.4 (the same water/cement ratio as that of the spheres).

Durability

Visual examination of the condition of the spheres and blocks and various concrete specimens taken from them revealed, in general, sound concrete with only occasional areas of slight loss of hardened paste from the outer one or two hundredths of an inch of the exterior surfaces of the uncoated spheres and the ocean-exposed blocks; there was no other visually apparent deterioration of the exterior surfaces nor of the concrete as seen on fractured surfaces.

Selected concrete samples were examined at NCEL by scanning electron microscope, including use of an electron probe to identify elements by energy-dispersive X-ray spectroscopy with particular attention paid to detection of magnesium, as described in Appendix C. A very small amount of magnesium was identified in a secondary deposit partially filling a small void 0.2 inch from the external uncoated surface of Sphere No. 18. Examination of the concrete fractured surface and of secondary deposits in voids near the interior surface of the sphere wall did not reveal any significant amount of magnesium. The configuration and amount of magnesium detected in the void near the outer surface of the sphere would not be expected to damage the concrete matrix nor weaken the strength of the concrete.

Table 7. Secant Coefficient of Permeability, K_c

Sphere No.	Hemisphere No.	Duration of Ocean Exposure (yr)	Depth, h (ft)	Sphere Interior Surface Area, A_s (ft^2)	Sphere Wall Thickness, t (ft)	Permeated Water, Q_p (ft^3)	Secant K_c (ft/sec)	Water/Cement Ratio	f'_c of "Wet" Control Cylinders at Time of Ocean Placement (psi)
12	W-32 W-29	5.3	2,790	72.5	0.344	1.24	1.25×10^{-14}	0.40 0.40	8,390 7,430
10	W-30 W-27	10.5	3,190	72.5	0.344	1.91	0.86×10^{-14}	0.39 0.42	8,560 8,330
18	W-42	10.5	1,840	36.2	0.344	0.37	0.58×10^{-14}	not known[a]	7,590

[a]Assumed to be in range of 0.38 to 0.42.

Pore size distribution and X-ray diffraction analyses were performed at the University of California, Berkeley on a cement paste sample exposed for 4 years in the ocean and a companion fog-room-exposed control specimen (Appendix A). No magnesium compounds were detected. X-ray diffraction data showed that 4 years of constant immersion in seawater had started a slight deterioration at the surface only and that the surface had become slightly weaker than that of the control cement paste sample.

Analysis of water that was recovered from inside Sphere No. 10 showed that the seawater that had permeated through the concrete wall of the sphere had been significantly changed (see Appendix D). The water from within the sphere had only one-fifth the salinity of representative seawater and a much lower specific gravity; it was strongly basic with a pH of 12.6. There were not only fewer dissolved salts but the proportions of the various ions differed greatly from seawater. It can be conjectured that some of the ions that had been filtered out by passage of the seawater through the concrete walls may have reacted with the cement. At this time there is no evidence of significant alteration of the concrete, but this behavior should be studied further.

Thus, it can be concluded that, although the ocean exposure produced slight effects on exterior surfaces, there was no significant deterioration of the concrete matrix of the spheres or blocks after 10.5 years in the ocean nor of the cement paste samples after 4 years in the ocean.

No visible corrosion was apparent on the steel reinforcing bars with a concrete cover of from less than 1.0 to greater than 2.5 inches in the wall of Sphere No. 18, which was under multiaxial compressive stress due to high pressure seawater at about 41°F with very low dissolved oxygen content (less than in 0.1 ml/l). This lack of corrosion was true even though in the uncoated lower hemisphere the concrete was saturated with seawater, which thus had been in direct contact with the reinforcing steel for a number of years.

FINDINGS

1. The uniaxial compressive strength of concrete exposed in the ocean for 10.5 years and tested in the saturated condition at a total age of 10.8 years was essentially the same strength as that of replicate concrete exposed 5.3 years in the ocean. The strength of concrete exposed in the ocean for 5.3 and 10.5 years was 15% greater than the strength of the reference 28-day fog-cured concrete, but about 15% less than the strength (at the same ages) of continuously fog-cured companion specimens, which averaged 35% above the 28-day strengths at both 5.6 and 10.8 years age.

2. Companion specimens exposed to a coastal atmosphere on land and tested in the air-dried condition were 12 and 5% stronger at 5.6 and 10.8 years age than the ocean-exposed concrete at the same ages. These differences are within the range in which a given concrete in the dry condition may be expected to be stronger than the same concrete (of the same age) in the wet condition. This demonstrates that the concrete

exposed in the ocean for more than 10 years was of comparable strength to good quality concrete exposed to typical on-land service conditions for the same length of time.

3. Two spheres were retrieved from the ocean after 10.5 years of sustained preloading of 30 and 52% of their ultimate strength and tested to failure under short-term loading in the laboratory. Their short-term implosion strengths, load/deformation curves, and failure modes were essentially the same as those of three spheres that had been preloaded 5.3 years. Also, their behavior was, in general, similar to that of nonpreloaded spheres except that all five ocean-loaded spheres were stronger and stiffer than the nonpreloaded spheres, which had been tested at a much younger age (about 0.5 year). The coated ("dry," i.e., partially saturated) spheres were consistently 10 to 20% stronger and averaged a 30% greater strain at failure than the uncoated saturated spheres. The short-term implosion pressure (failure loading), P_{im}, of the spheres, regardless of conditions of preloaded or nonpreloaded, or wet or dry concrete, showed a consistent value relative to the uniaxial compressive strength, f'_c, of the concrete at the time of testing; the value of P_{im} averaged 30% of f'_c and ranged from 28 to 32% of f'_c.

4. None of the spheres in the ocean are known to have imploded after the three spheres previously reported to have imploded at the time of deployment or prior to their first inspection (1.2 or 3 years in the ocean). Two spheres leaked but did not implode: one of these leaked at the time of deployment or shortly thereafter; the other one failed locally (possibly at a through-hull penetration) after 9.6 years in the ocean. Seven spheres remain intact in the ocean under continuous long-term loading of 30 to 70% of their predicted short-term strength.

5. Although the coated spheres absorbed small amounts of water, the waterproofing coating prevented water from permeating through the concrete walls into the interiors, which remain dry. Permeation of water through the walls of the uncoated (bare concrete) spheres continues at a very slow rate in some spheres. Retrieved uncoated spheres contained from 0.4 to 1.9 ft^3 of free water; uncoated spheres still in the ocean are estimated to contain from 1.6 to 3.2 ft^3 of free water.

6. There was slight deterioration of the concrete at the ocean-exposed surfaces, but otherwise there was no apparent significant physical or chemical deterioration of the concrete, nor any visible corrosion of reinforcing steel (with concrete cover less than 1 inch in some cases) after 10.5 years of deep ocean exposure.

7. Considerable biological fouling is present on both coated and uncoated concrete. The rate of biological growth is increasing with time.

SUMMARY

By means of long-term deep-ocean exposure, in-situ inspection, and laboratory testing of retrieved specimens, experimental data have been

obtained on the compressive strength behavior, permeability, and durability of pressure-resistant concrete structural models (concrete spheres 66 inches in outside diameter and 4.12 inches wall thickness) subjected to continuously sustained hydrostatic loading. The results after 13 years of ocean exposure provide a basis for guidelines, within usually acceptable limits for predicting performance of materials and structures, for engineering design of undersea concrete structures.

For the type of concrete used in this program, with a water/cement ratio of 0.40 and a nominal 28-day compressive strength of 8,000 psi, the major results can be summarized as follows:

1. Concrete exhibits good strength characteristics for ocean applications. For concrete spherical structures that are to be subjected to sustained pressure in the ocean for the lengths of time covered in this study, the critical period is the time of deployment through the early period (for several months up to 1 year) in the ocean; during and after this early period, good quality concrete can be expected to gain and maintain its compressive strength.

2. Concrete under multiaxial compressive stress is a durable material in the deep ocean; neither deterioration of the concrete matrix nor corrosion of reinforcing steel are apparent problems, even though the concrete becomes saturated with seawater.

3. Uncoated (bare) concrete has a very low rate of permeation of seawater through the concrete, even under sustained high pressure. If desired, this small flow can be prevented by using a waterproofing coating. Also, provided there is enough curing water available to hydrate the cement, a coating will permit the concrete to maintain a higher strength by limiting the degree of saturation of the hardened concrete.

ACKNOWLEDGMENTS

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Appendix A

MICROSTRUCTURAL EXAMINATION OF CEMENT PASTE SAMPLES

A supplemental study of possible chemical changes of hydrated cement in seawater (in particular, replacement of calcium ions, Ca^{++}, in tobermorite gel by magnesium ions, Mg^{++}, from the seawater) was started in 1978. Cement paste samples, each 1 inch in diameter by 2 inches long, were prepared by Prof. P.K. Mehta, University of California, Berkeley. Ten of these were placed in the ocean, five each at Sphere No. 15 (water depth, 2,300 feet) and 16 (2,120 feet) in March 1978. Control specimens were stored in the fog room at 100% relative humidity and 73°F. Information on chemical composition of the paste samples and their deployment in the ocean and retrieval in March 1982 is given in Appendix D of Reference 2 and in the main text of this report.

X-ray diffraction and pore size distribution analyses were performed on an ocean-exposed and a control specimen by Prof. Mehta. The X-ray diffraction data show that 4 years of constant immersion in seawater has started a slight deterioration at the surface only. A reduction in the calcium hydroxide content and formation of hydrocalumite (carbonated calcium aluminate hydrate) was noticed. A sample about 1/4 inch away from the surface showed that the pore size distribution was somewhat finer than that of the control cement paste, thus indicating formation of some reaction products that filled the pores. Although no magnesium compounds were detected, it appears that the surface of the test specimen has become slightly weaker than the control cement paste.

Appendix B

DESCRIPTION OF EXPOSURE ENVIRONMENTS

To obtain comparative data on the compressive strength and other material properties of the concrete samples, they were, after the initial moist cure, exposed in three different environments: in the ocean at water depths of 1,830 to 5,100 feet, outdoors on land about 150 feet from the shoreline, and in a conventional moist environment "fog room." Cement paste samples were exposed in the ocean (at 2,100- and 2,300-foot depths) and in the fog room.

The most important factors that differed in the three environments were: the characteristics of the water (moisture) available at the external surface of the specimens, the extent of the availability of this moisture, the contact medium (air or water), the ambient temperatures, and the ambient pressure. These items are tabulated in Table B-1.

For the ocean-exposed and the fog-room-exposed specimens, the conditions were constant throughout the exposure period. For the on-land, field-cured specimens, the conditions (except for atmospheric pressure) varied significantly on a diurnal, seasonal, and year-to-year basis. The temperature and relative humidity descriptions are estimates (no continuous temperature or relative humidity measurements were made) based on meteorological records for a nearby coastal locality (Ref 5). The average maximum and minimum daily temperatures were 67 and 51°F, each with a standard deviation of about 7°F. Outdoor temperatures were above 80 or below 36°F, less than about 1% of the time each. The overall average near 59°F is intermediate between the fog room and ocean temperatures that were essentially constant at 73 and 42°F, respectively.

Available moisture for the outdoor specimens varied considerably, ranging from the free water of frequent natural fog and dew (many days throughout the year, especially during the night and early morning) and seasonal winter rains (10 to 30 days per year), to average relative humidities of 74%, to the loss of moisture from the specimens during seasonal periods of low relative humidity, especially when associated with a several-day period of hot, dry winds (10 to 20 days per year). Overall, the relative humidity was greater than 80% for 45% of the time and less than 20% for 4% of the time.

The fog-room- and ocean-exposed specimens are assumed to have water continuously available for continuing hydration of the cement. The on-land, field-exposed, air-dried specimens, on the other hand, are assumed to have water available for hydration only during those times that either free water (dew, rain) was available at the surface or the relative humidity was greater than 80% (Ref 6), which, though frequent, was still less than one-half of the total time.

Thus, the fog-room- and ocean-exposed specimens are considered to be saturated. The ocean-exposed concrete block specimens are assumed to correspond to the concrete in the uncoated spheres, which is also considered to be saturated as evidenced by the free water found inside the

retrieved uncoated spheres. The on-land, field-exposed, air-dried specimens are considered to be only partially saturated (and were tested for uniaxial compressive strength in that condition); the air-dried specimens correspond, roughly, to the condition of the concrete in the coated spheres, which were considered not to have become completely saturated in the ocean as evidenced by the absence of any free water on the interior of the two coated spheres removed from the ocean after 5.6 years of exposure.*

*After the initial 28-day moist cure, all the hemispheres and (after their fabrication) the spheres were field-cured (i.e., air-dried) for several weeks to several months before being placed in the ocean.

Table B-1. Nominal Exposure Conditions for Concrete Specimens Used for Compressive Strength Tests

Type of Specimens and General Description	Dominant Ambient Exposure Medium (After Initial 28-Day Moist Cure)	Availability of Water at Surface of Concrete	Ambient Pressure (psi)	Ambient Temperature (°F)	Assumed Moisture Condition of Concrete at Time of Compressive Strength Tests
Fog-cured 6- by 12-in. cast cylinders continuously exposed in environmentally controlled moist room	Air with freshwater artificial mist	Continuous 100% relative humidity plus free water	14.7	Constant 73°F±3°	Saturated
On-land field exposed 18- by 18- by 14-in. blocks[a] placed outdoors about 150 ft from the ocean	Marine atmosphere with natural moisture (including some dissolved "salt"); varied from frequent natural fog and dew (and occasional rain) to occasional dry wind	Variable; relative humidity greater than 80% for 45% of the time, less than 20% for 4% of the time, with overall average of 74%	14.7	Variable; typically between 50 and 67°F, >80°F or <36°F less than 1% of the time; overall average 59°F	Air-dried (i.e., partially saturated)
Ocean exposed 18- by 18- by 14-in. blocks[a] submerged at various depths in the ocean from 1,840 to 4,330 ft	Seawater with very low dissolved oxygen content	Continuously wet	Variable from one specimen to another, 820 to 1,930 psi, but constant for a given specimen	Constant 41 to 42°F	Saturated

[a]Four nominally 6- by 12-in. cores were drilled from each block just prior to compressive strength tests.

Appendix C

MICROSTRUCTURAL EXAMINATION OF CONCRETE SAMPLES

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Metallurgist
Naval Civil Engineering Laboratory (NCEL)

Samples of concrete from the lower (uncoated) hemisphere of Sphere No. 18 and its associated ocean-exposed block were examined at NCEL by scanning electron microscopy. Elemental analysis of selected areas was performed by energy-dispersive X-ray spectroscopy. Particular attention was paid to the detection of magnesium. It has been conjectured that Mg^{++} ions in seawater may react with the calcium hydroxide in concrete exposed to seawater and that brucite (magnesium hydroxide) may precipitate, partially blocking pores and reducing permeability. To obtain micrographs, the samples were sputter-coated to avoid surface "charging" effects; this accounts for the peaks at gold X-ray energy levels in the spectra.

Spectrum C1 is a "bulk" analysis at an area of a cross section of the 4.12-inch-thick wall of the lower, uncoated portion of Sphere No. 18 about 0.2 inch from the external surface of the sphere. A small magnesium peak was generated; however, the concentration of this element is very low relative to the detectability limit, and the results of cross-sectional scans would be debatable with present instrumentation.

When the concrete is broken open, small internal voids are seen. On the surfaces of these voids are deposits that apparently were built up by intrusion through micropores into the voids. Figure C-1 depicts a void about 0.2 inch from the external (ocean-exposed) surface of Sphere No. 18. Figure C-2 is a higher magnification view of the internal deposit within this void. Elemental analysis indicates that the primary detectable component of this material is magnesium (see Spectrum C2).

Figure C-3 depicts a void approximately 0.4 inch from the interior surface of the wall of the sphere. At this location the deposit on the surface of the void, shown in Figure C-4, does not have a detectable magnesium content (see Spectrum C3).

The implosion in the pressure vessel of the spheres produced a number of very thin pop-outs (typically about 1 inch in diameter) scattered over the exterior surface of the sphere. A white deposit was frequently observed on the fractured faces of these pop-outs. X-ray analysis of the fractured (internal) face of one of these pop-outs revealed a sulfur peak, generated by the white deposit on the face, in addition to the expected peaks for concrete (see Spectrum C4).

A void in a fractured piece of a cylinder cored from an ocean-exposed block was also examined. As shown by Figures C-5 and C-6, long needle-shaped crystals have formed inside the void. Spectrum C5 indicates this is a sulfur-containing compound. No magnesium was detected; however, the distance of the void from the exposed surface of the block is not known.

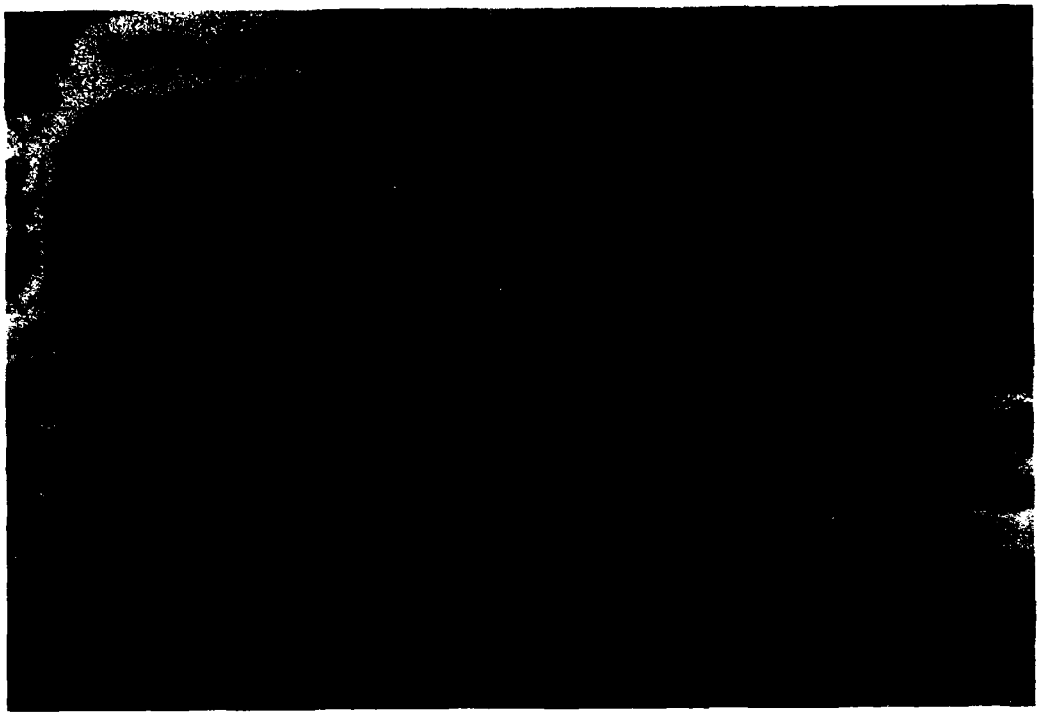


Figure C-1. Void in broken concrete wall (broken just prior to examination) at a location about 0.2 in. from external surface of sphere. (Magnification 7x)

Figure C-2. Higher magnification (270x) view of surface of voids in Figure C-1.

Figure C-3. Void about 0.4 in. from interior surface of sphere wall. (Magnification 13x)

Figure C-4. Higher magnification view (250x) of surface of void in Figure C-3.

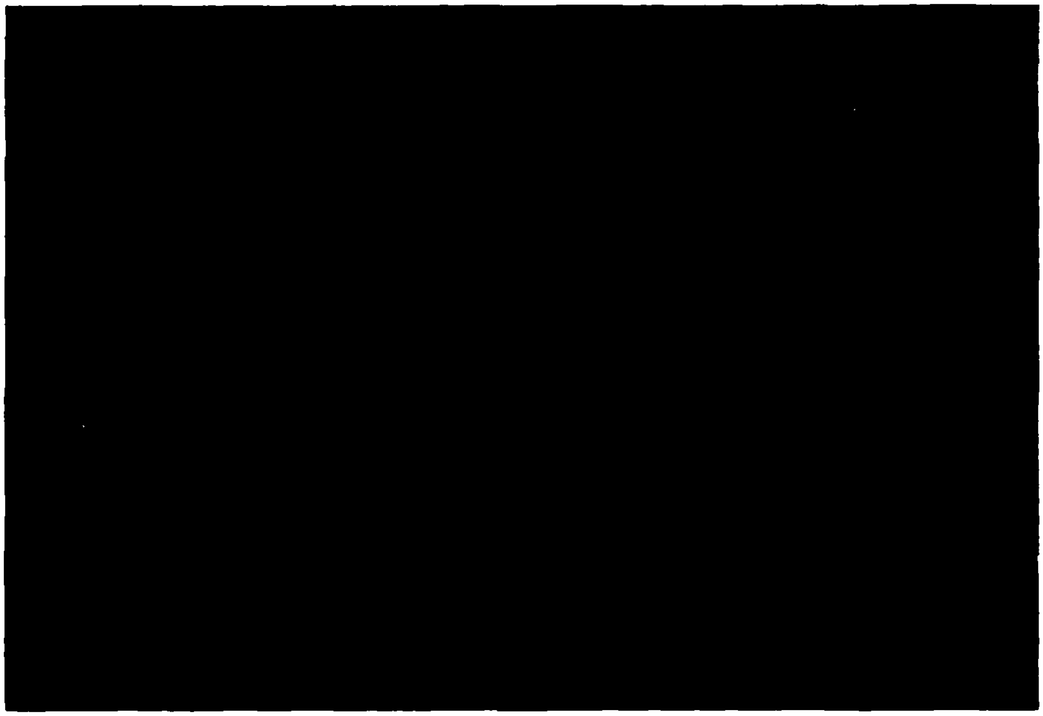


Figure C-5. Void in fractured piece (after compression test) of cored cylinder 18-S3. (Magnification 25x)

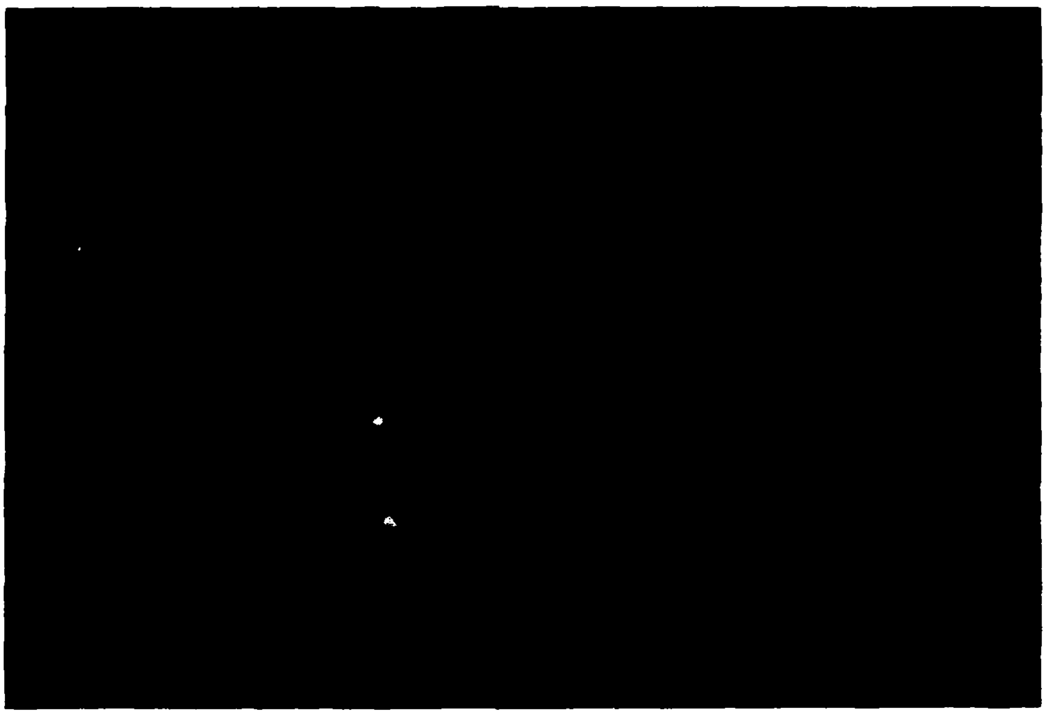
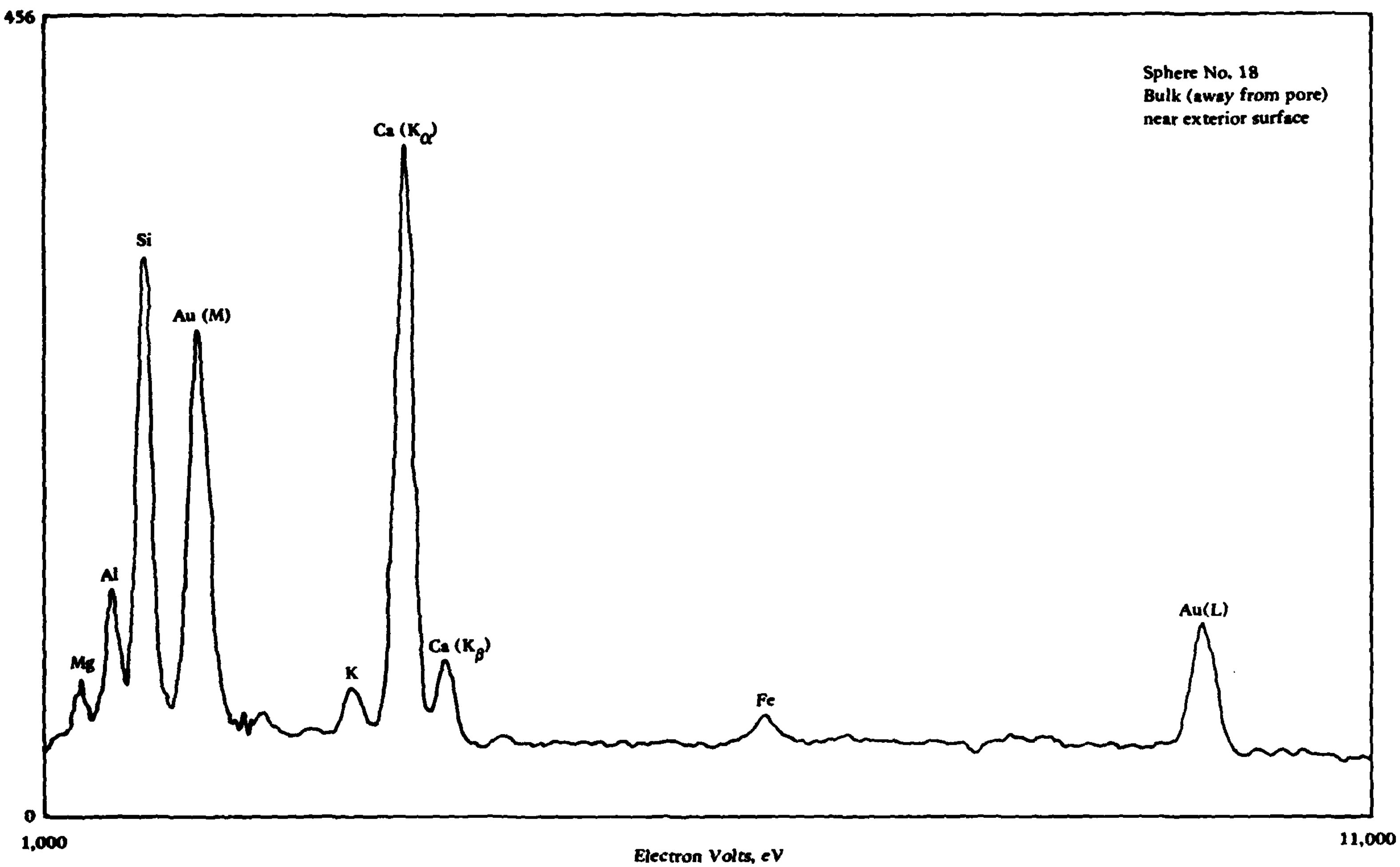
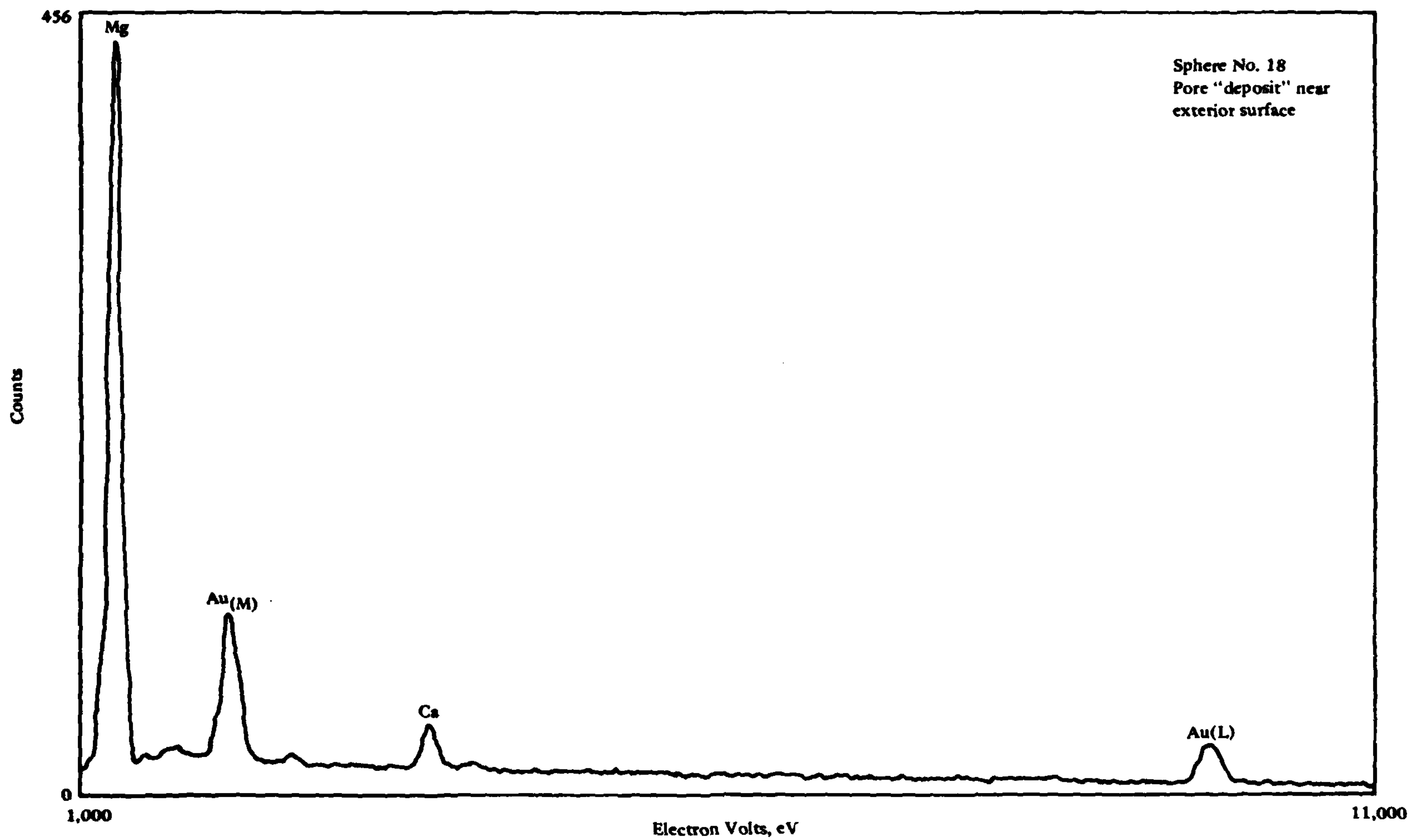


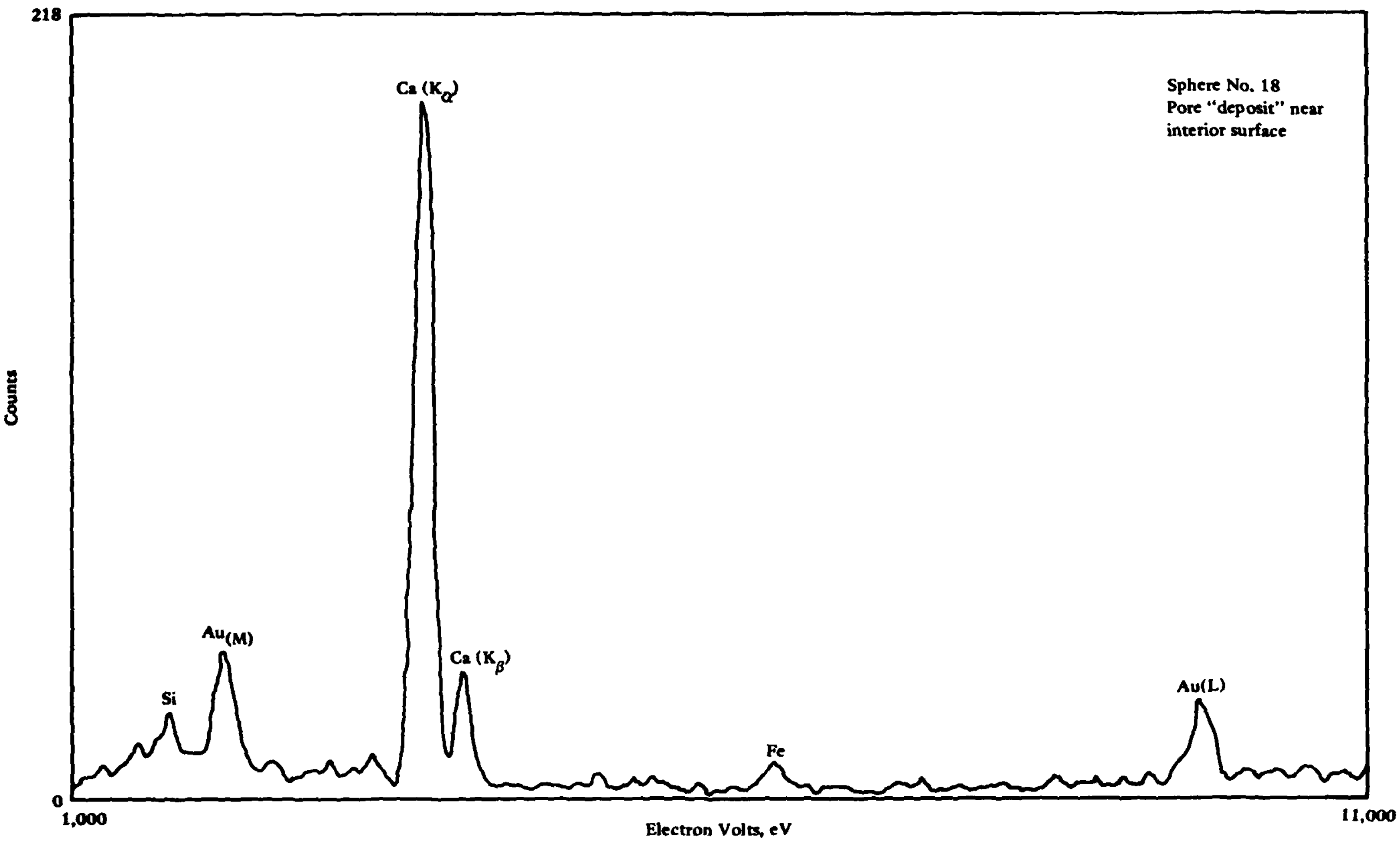
Figure C-6. Higher magnification view (250x) of crystals in Figure C-5.


456
0
Counts
1,000
11,000
Electron Volts, eV
Sphere No. 18
Bulk (away from pore)
near exterior surface
Mg
Al
Si
Au (M)
K
Ca (K$_\alpha$)
Ca (K$_\beta$)
Fe
Au(L)

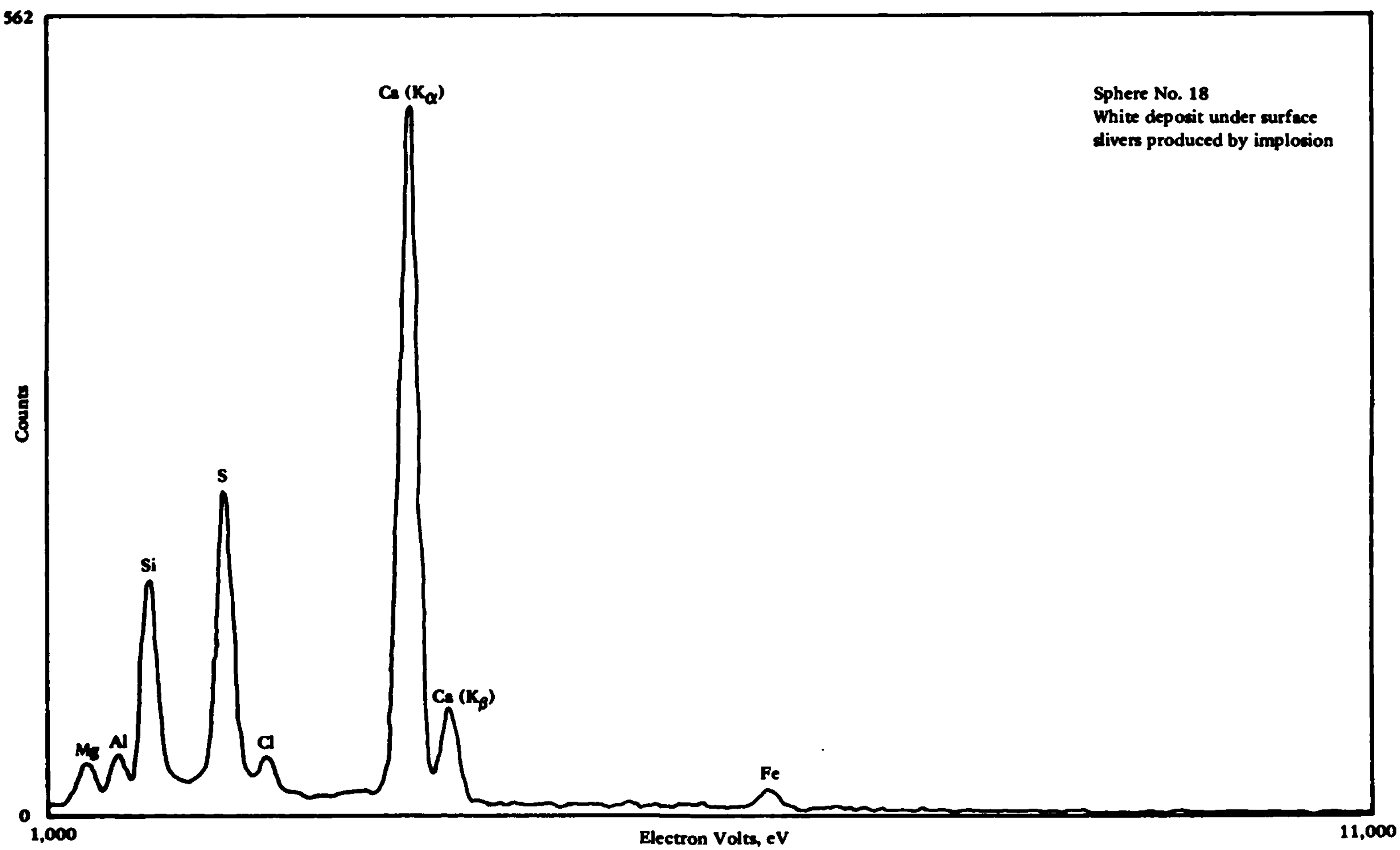
Spectrum C1


456
Mg
Sphere No. 18
Pore "deposit" near
exterior surface
Counts
Au(M)
Ca
Au(L)
0
1,000
11,000
Electron Volts, eV

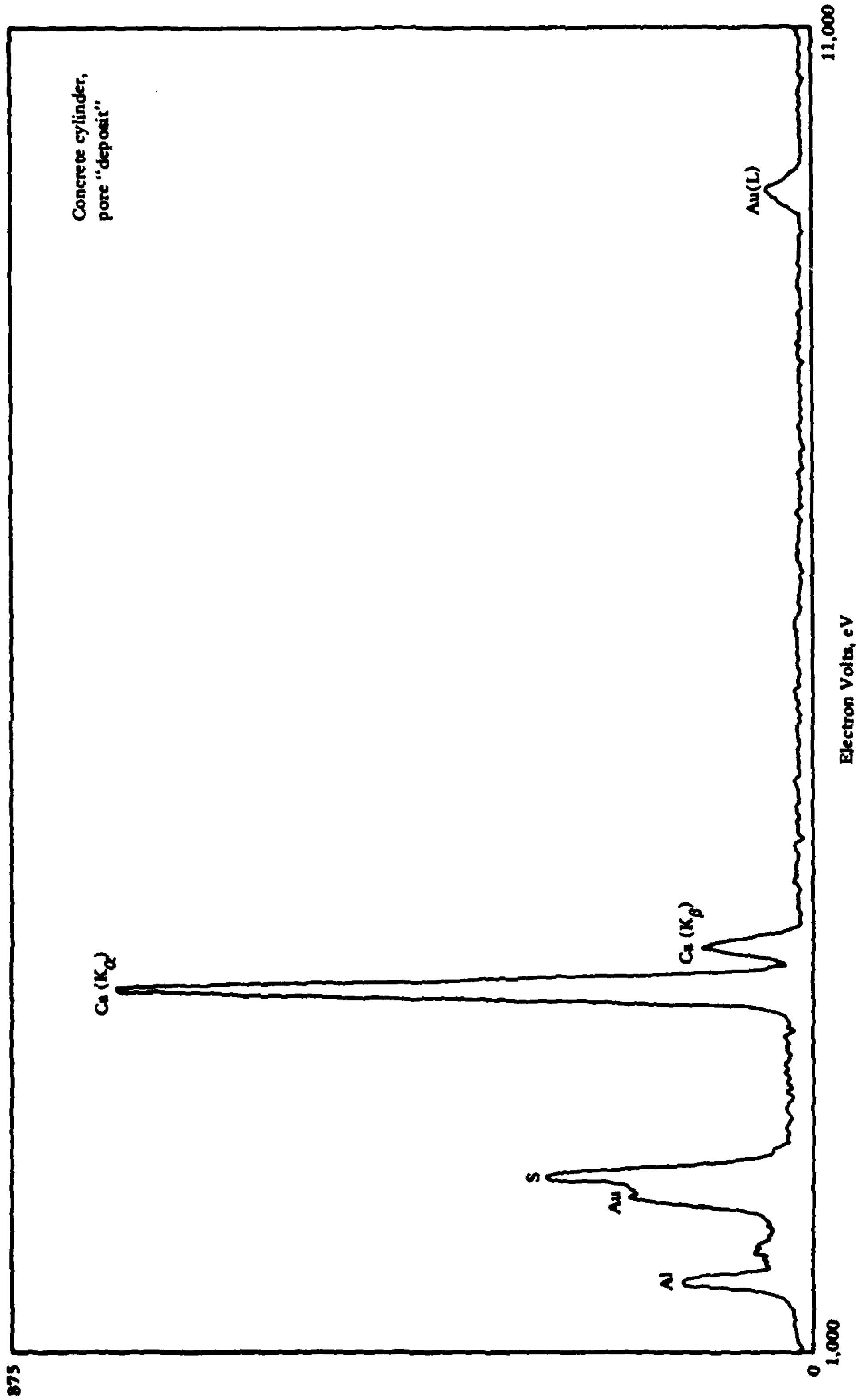
Spectrum C2


218
0
Counts
1,000
11,000
Electron Volts, eV
Ca (Kα)
Ca (Kβ)
Au(M)
Si
Fe
Au(L)
Sphere No. 18
Pore "deposit" near
interior surface

Spectrum C3


562
Counts
0
1,000
Electron Volts, eV
11,000
Sphere No. 18
White deposit under surface
slivers produced by implosion
Mg
Al
Si
S
Cl
Ca (K_α)
Ca (K_β)
Fe

Spectrum C4


Concrete cylinder,
pore "deposit"
875
0
1,000
11,000
Electron Volts, eV
Al
Au
S
Ca (K_α)
Ca (K_β)
Au(L)

Spectrum C5

Appendix D

EXAMINATION OF PERMEATED WATER

A sample of the water removed from the interior of Sphere No. 10 was analyzed by Jacobs Environmental, a commercial laboratory in Ventura, Calif., in accordance with Standard Methods for the Examination of Water and Wastewater, 15th edition, 1980. The results are shown in Table D-1. Note that this water does not have the proportions of dissolved constituents nor other characteristics of representative seawater.

The most notable differences are that: (1) the water from the sphere has only one-fifth the salinity of seawater and, concomitantly, a lower specific gravity; (2) the sphere water with a pH of 12.6 is strongly basic; and (3) compared to seawater, it has a high proportion of potassium, carbonate, and hydroxyl ions, a low proportion of sodium and sulfate ions, and a near absence of chloride and magnesium ions. It can be conjectured that the 4.12-inch-thick concrete wall of the sphere may act somewhat as a semipermeable membrane permitting small amounts of water to pass through with a certain amount of selective filtering out of some ions and molecules. Also, it can be conjectured that various ions in the seawater may have reacted with the constituents of the concrete, for example, the hydrated cement products (i.e., hydrated silicates, aluminates, and ferrites, and calcium hydroxide).

Solid particulate matter filtered from the water found inside Sphere No. 10 was analyzed at the Naval Civil Engineering Laboratory by energy-dispersive X-ray spectroscopy. As shown in Figure D-1, a major peak was generated for calcium. Smaller amounts of silicon, aluminum, magnesium, iron, zinc, chlorine, sulfur, and potassium were also detected. Determination of elemental concentration from peak height (i.e., total counts) is only semiquantitative since corrections have not been made for atomic number, absorption, or fluorescence. Major elements found in concrete appear to be present. Also present are elements of the major dissolved salts found in seawater, with the exception of sodium, which cannot be detected by the employed equipment due to sodium's low atomic number. The lower limit of detectability over the range of the other elements observed is about 0.1%.

Table D-1. Analysis of Water Recovered from Inside Sphere No. 10[a]

Constituent	Water From Sphere No. 10[b] Milligrams Per Liter (ppm)	Water From Sphere No. 10[b] Milli-Equivalents Per Liter	Representative Seawater[c] Milligrams Per Liter (ppm)	Representative Seawater[c] Milli-Equivalents Per Liter
Cations				
Ammonium, NH_4	6	0.33	0.8	0.04
Sodium, Na	1,230	53.50	10,600	461.1
Potassium, K	2,900	74.15	380	9.72
Calcium, Ca	11	0.55	400	19.96
Magnesium, Mg	14	1.15	1,280	105.29
Barium, Ba	--	--	0.05	--
Subtotal for Cations:	4,161	129.68	12,661	596.11
Anions				
Sulfate, SO_4	160	3.33	2,560	53.32
Chloride, Cl	53	1.50	19,200	541.63
Carbonate, CO_3	2,640	88.12	<0.1	--
Bicarbonate, HCO_3	<0.1	--	142	2.33
Hydroxide, OH	590	34.70	<0.1	--
Iodide, I	<0.1	--	<0.1	--
Sulfide Ion, HS	<0.1	--	<0.1	--
Sulfite, SO_3	<0.1	--	1.3	0.07
Fluoride, F	1.3	0.07	0.5	0.01
Nitrate, NO_3	154	2.48		
Bromide, Br				
Subtotal for Anions:	3,598	130.20	21,904	597.36
Total Cations + Anions:	7,759		34,565	
Other				
Silica, SiO_2	1.0		0.05	
Boron, as B	2.1		4.6	
Iron, Fe	0.08		<0.01	
Manganese, Mn	0.03		<0.01	
Volatile Acids (as Acetic)	<10		<10	
Carbon Dioxide, CO_2	--			
Total Dissolved Minerals (by addition: $HCO_3 \rightarrow CO_3$)	6,150		34,500	

[a]Adapted from Laboratory Report Number V8203203 and associated correspondence by Jacobs Environmental, Ventura, Calif.

[b]Specific gravity = 1.0005; pH = 12.6; Resistivity (at 77°F) = 130 ohms/cm; Salinity = 7.4 ppt.

[c]Specific gravity = 1.026; pH = 8.4; Resistivity (at 77°F) = 23 ohms/cm; Salinity = 35 ppt.

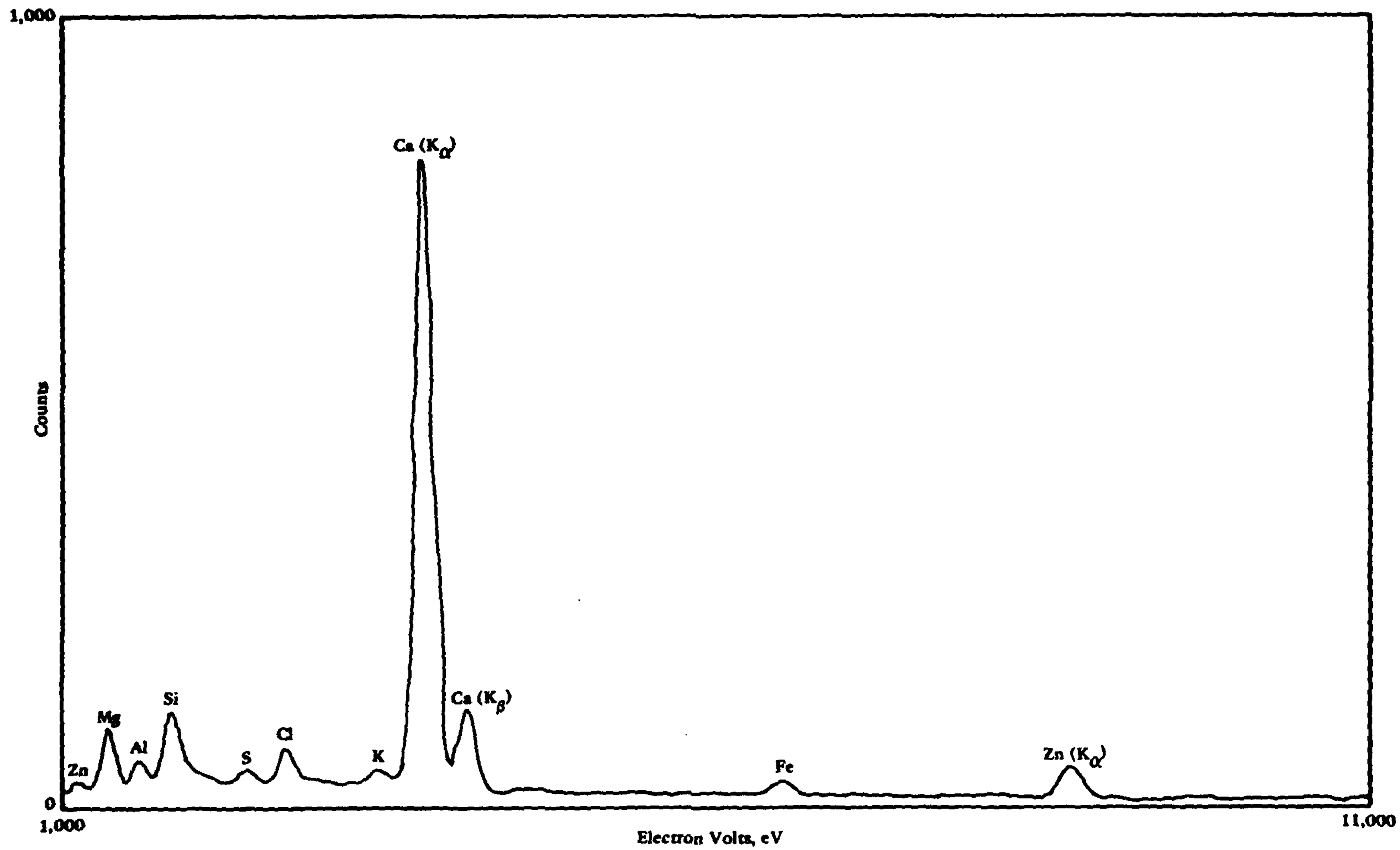


Figure D-1. Energy-dispersive X-ray spectrum of particulate matter filtered from permeated water inside spheres.

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